Atacama
Large
Millimeter /
submillimeter
Array

Final Report of the Signal Chain Working Group

ALMA-05.00.00.00-0051-A-REP

2021-09-29

Prepared by:	Organization:	Signature:
Todd Hunter	NRAO	
Christophe Jacques	NRAO	
Seiji Kameno	JAO	
Takafumi Kojima	NAOJ	
Hiroshi Nagai	NAOJ	
Takeshi Okuda	JAO	
Neil Phillips	ESO	
Gie Han Tan (Chair)	ESO	
Released by:	**Organization:**	**Signature:**
Stuartt Corder (ALMA Deputy Director)	JAO	

Change Record

Version	Date	Affected Section(s)	Author	Reason/Initiation/Remarks
A.0	2021-05-19	All		Initial draft
A.1	2021-09-24	All		Final working draft for SCWG internal review
A.2	2021-09-29	All		Final working draft submitted to AMT

Table of Contents

Executive Summary

This report is the second deliverable of the Signal Chain Requirements Working Group (SCWG) as defined in the corresponding charter [AD2]. It comprises the working group responses to the technical charges defined by the AMT in this charter. Analyses of these charges are presented in Chapter 2. The recommended key requirements at product Level 0 and 1 have been summarized in Chapter 1 so that they can be easily implemented in an update of the ALMA Project System-Level Technical Requirements [RD28] and flow down in individual sub-system Technical Specification documents.

This document builds upon the preliminary report [RD4] prepared by the SCWG in February 2021. This preliminary report was distributed among AMT, Correlator Working Group, Front-end/Digitizer Working Group and the ALMA Control Software Lead. The feedback received from these key stakeholders and the corresponding discussions provided important input for the SCWG which has been addressed in this document. We are indebted to these stakeholders for the time and effort spent on their feedback and the many constructive discussions that very much helped in preparing this report.

Our main conclusions and recommendations are summarized by the following points:

- The SCWG strongly supports the key recommendations by the Correlator Working Group and the Front-end/Digitizer Working Group. Still a full analysis from the top level system point of view is strongly advised to confirm the recommendations by the three working groups are consistent and compatible;
- Location of the 2nd Gen Correlator at the OSF is highly recommended for a cost effective construction and operations of the Observatory. The working group has assessed the impact and costs of a new optical fiber cable between AOS site and OSF building in considerable detail and found that this investment is relatively minor, on the order of US$ 2.6M, while the benefits are substantial;
- Deployment of the 2nd Gen Correlator, DTS, Digitizers, and supporting software can only be done in parallel to the existing, operational, observing system to meet the condition of a down time with an acceptable level, at most a few months. Location of the 2nd Gen Correlator at the OSF and a new optical fibre cable between AOS and OSF are essential conditions for such a parallel deployment;
- Integrating the 2nd Generation Correlator design and construction as proposed by the NA ALMA Executive in the ALMA 2030 upgrade and system architecture is a complex matter and sufficient time and effort should be dedicated to make well founded decisions by the ALMA Partnership. As much as feasible within the given time and information available to the SCWG we have made a preliminary impact analysis of the 2nd Generation Correlator design (chapter 4);
- Last, but certainly not least, it is urged that the requirements recommended by the various working groups are reviewed, formalized and issued in updated specification documents. The review of these recommended requirements should be done from a holistic system point of view against the ALMA 2030 science objectives. This is especially urgent with the NA 2nd Generation Correlator design and construction proposal in mind to which the SCWG was given limited access while finishing this report. We expect that a proper top-down strategy following established ALMA PA processes will lead to a satisfactory outcome.

1 Introduction

1.1 Purpose

This report provides a comprehensive response for each of the charges to the Signal Chain Requirements Working Group as defined in [AD2]. Requested recommendations on sub-system and interface key requirements Preliminary are presented in this document.

1.2 Scope

The contents of this report focus on system architecture aspects and specifications for the backend, data transmission, and the part of the system between FE to Correlator sub-systems. This is consistent with the ALMA 2030 roadmap objectives and with the specifications of the other working groups, and minimizing changes to existing systems and infrastructure [AD2].

1.3 Applicable Documents

The following documents are part of this document to the extent specified herein. If not explicitly stated otherwise, the latest issue of the document is valid.

Ref	Document Title	ALMA Doc. Number
AD1	The ALMA Development Roadmap	AEDM 2017-021-O
AD2	Charter for the Updated Signal Chain Requirements Working Group	ALMA-50.00.00.00-0833-A-SPE
AD3	ALMA System Technical Requirements, rev C	ALMA-80.04.00.00-005-C-SPE
AD4	ALMA System Block Diagram, version R	SYSE-80.04.01.00-004-R-DWG

1.4 Reference Documents

The following documents contain additional information.

Ref	Document Title	ALMA Doc. Number
RD1	Specifications for a Second-Generation ALMA Correlator [Working Group Report] (Draft version 2021-01-08)	ALMA-05.00.00.00-0049-A-SPE
RD2	Report of the ALMA Frontend & Digitizer Specification Working Group	ALMA-05.00.00.00-0048-A-REP
RD3	Report to the ALMA Management Team “The ALMA 2030 Vision: Design considerations for Digitizers, Backend and Data Transmission System”	14-16 Oct. 2020

Ref	Document Title	ALMA Doc. Number
RD4	Preliminary Report on System Considerations relevant to the Correlator Working Group	ALMA-05.00.00.00-0050-A-REP
RD5	Upgrading the ALMA Digital System, from Digitization to Correlation Mid-term Report	LAB / UdB, 22 Jan. 2021
RD6	The ALMA Phasing System: A Beamforming Capability for Ultra-high-resolution Science at (Sub)Millimeter Wavelength	L. D. Matthews et al. (2018), PASP, 130:015002
RD7	VLBI Data Interchange Format (VDIF) Specification	https://vlbi.org/vlbi-standards/vdif/
RD8	Incoherent clocking in coherent radio interferometers	Carlson, B., Electronics Letters 12th July 2018, Vol. 54, No. 14, pp. 909–911
RD9	The CloudSat Radar and Implications for ALMA	ALMA Memo 504
RD10	MeerKAT data distribution network	Martin J. Slabber, Jason Manley, Joyce Mwangama, Neco Ventura, Proc. SPIE 10707, Software and Cyberinfrastructure for Astronomy V, 107070H (6 July 2018); doi: 10.1117/12.2311870
RD11	ALMA Power Costs and non-ALMA project	ALMA-20.05.01.00-0044-A-REP
RD12	IMG Energy and Quality Reports - Parent Ticket	IMG-31
RD13	64 Antenna Correlator Specifications and Requirements	ALMA-60.00.00.00-001-C-SPE
RD14	Interface Control Document Between: AOS Technical Building And: Baseline Correlator	ALMA-20.01.02.00-60.00.00.00-A-ICD
RD15	Interface Control Document Between: Site (AOS Technical Building) And: ACA Correlator	ALMA-20.01.02.00-62.00.00.00-B-ICD
RD16	Interface Control Document Between: Site (AOS Technical Building) And: ACA Correlator	ALMA-20.01.02.00-62.00.00.00-C-ICD
RD17	Interface Control Document Between: ACA Correlator And: ACA Spectrometer	ALMA-62.00.00.00-64.00.00.00-A-ICD
RD18	Study Report on Cooling Capacity of ACA Correlator Room for ACA Spectrometer	CORL-64.00.00.00-0013-A-REP
RD19	Indoor Sports Facility at ALMA OSF Design and Construction DEMAND STUDY & FEEDER CALCULATION ELECTRICAL	ALMA-20.08.15.07-0010-A-REP
RD20	ALMA HIL Simulation Environment Final Design Report	ALMA-05-13.00.00-023-A-REP
RD21	Interface Control Document From: Site To: 2-Antenna Correlator	ALMA-20.00.00.00-63.00.00.00-A-ICD
RD22	Interface Control Document Between: Antenna Subsystem And: Back End Subsystems	ALMA-34.00.00.00-50.00.00.00-D-ICD
RD23	Back End Electronics Design Description	BEND-50.00.00.00-077-B-DSN
RD24	Correlator Room HVAC Study	SITE-20.01.02.00-002-A-REP
RD25	ALMA Product Tree	ALMA-80.03.00.00-001-T-LIS
RD26	Technical Requirements for the Back End Subsystem	ALMA-50.00.00.00-092-C-SPE

Ref	Document Title	ALMA Doc. Number
RD27	ALMA Development Studies 2019: Upgrading the ALMA Digital System, from Digitization to Correlation Final Report	July 16th, 2021
RD28	ALMA Project System-Level Technical Requirements	ALMA-80.04.00.00-005-C-SPE
RD29	IF Switch Module Technical Specifications	FEND-40.08.01.00-001-A-SPE
RD30	ALMA Back End IPT IF Downconverter Production Specification	BEND-52.06.00.00-003-C-SPE
RD31	Interface Control Document Between: Front End / IF And: Back End / IF Downconverter	ALMA- 40.08.00.00-52.00.00.00-A-ICD
RD32	Interface Control Document Between Front End First Local Oscillator And Back End LO References	ALMA-40.10.00.00-56.00.00.00-D-ICD
RD33	ALMA Reviews Definitions, Guidelines and Procedure	ALMA-80.09.00.00-001-E-PLA
RD34	ALMA Project Review of the HVAC design of the OSF Technical Facility	SITE-20.08.10.00-008-A-REP
RD35	ALMA Specification Document Tree	ALMA-80.14.00.00-002-B-LIS
RD36	ALMA High-frequency Long-baseline Campaign in 2017: A Comparison of the Band-to-band and In-band Phase Calibration Techniques and Phase-calibrator Separation Angles	Maud et al. 2020, ApJS, 250, 18, 10.3847/1538-4365/abab94
RD37	ALMA High-frequency Long Baseline Campaign in 2017: Band-to-band Phase Referencing in Submillimeter Waves	Asaki et al. 2020, ApJS, 247, 23, 10.3847/1538-4365/ab6b20
RD38	High-precision Astrometric Millimeter Very Long Baseline Interferometry Using a New Method for Atmospheric Calibration	Rioja & Dodson, 2011, AJ, 141, 114, 10.1088/0004-6256/141/4/11
RD39	ALMA Cycle 8 2021 Technical Handbook	Doc 8.5, ver. 1.0 | 15 March, 2021
RD40	Intel / Altera Whitepaper: FPGA Product Support and EOL as Past Performance Indicators	WP-01216-1.0
RD41	Primer: Consolidated and simplified ALMA TALON correlator/beamformer (AT.CBF) description for discussions with the ALMA signal chain working group	VDRAFT-11, 2021-08-01
RD42	Discussion memo: ALMA 2030 Digitizer/New “AT.CBF” correlator inter-operability/ compatibility issues	VDRAFT-6, 2021-08-15
RD43	Convenient formulas for quantization efficiency	Thompson, Emerson & Schwab, 2007, Radio Science, Vol 42, p. 3022
RD44	Front End IF Switch Assembly Design Report	FEND-40.08.01.00-004-A-REP

1.5 Acronyms

The acronyms used in this document are listed below.

2SB	Two Sideband (sideband separating)
ABM	Antenna Bus Master
ACA	Atacama Compact Array
ACAS	ACA Spectrometer
ACS	ALMA Common Software
AIVC	Assembly, Integration, Verification and Commissioning
AD	Applicable Document
ADC	Analog to Digital Converter
ALMA	Atacama Large Millimeter/Submillimeter Array
AMT	ALMA Management Team
AOS	Array Operations Site
API	Application Programming Interface
APDM	ALMA Project Data Model
APP	ALMA Phasing Project
ARC	ALMA Regional Center
ARTM	Array Real Time Machine (M&C for all CLOA equipment)
ASC	ALMA Sensitivity Calculator
ASDM	ALMA Science Data Model
BE	Back-End
BER	Bit Error Rate
CAN	Controller Area Network
CARTA	Cube Analysis and Rendering Tool for Astronomy
CCA	Cold Cartridge Assembly
CCB	Change Control Board
CCC	Correlator Control Computer
CD	Chromatic Dispersion
CDR	Critical Design Review
CDMR	Critical Design and Manufacturing Readiness Review
CFP	100G Form factor Pluggable
CLOA	Central Local Oscillator reference for ALMA
CORBA	Common Object Request Broker Architecture
COTS	Commercial Off-The-Shelf
CRE	Change Request
CRG	Central Reference Generator
CVR	Central Variable Reference (signal generator in each photonic reference)
DCI	Data Center Interconnects
DGCK	Digital Clock
DMC	DRX Monitor & Control computer
DSB	Double Sideband
DSP	Digital Signal Processor
DSO	Department of Science Operations
DTS	Data Transmission System
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fiber Amplifier

EDM	Electronic Document Management System
EMC	Electro-Magnetic Compatibility
ENOB	Effective Number of Bits
EOC	Extension of Capabilities
EOL	End of Life
ESO	European Southern Observatory
F2F	Face-to-face
FE	Front-End
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FLOOG	First Local Oscillator Offset Generator
FOAD	Fiber Optic Amplifier and Demultiplexer
FOM	Fiber Optic DWDM Multiplexer
FOMA	BE Fiber Optic Management Article (external & internal fibers, patch panel, FOAD, and racks)
FOTS	Fiber Optic Transmission Subsystem
FPGA	Field Programmable Gate Array
FX	Fourier transform correlation type correlator
GT	Gas Turbine
HiL	Hardware in the Loop
HVAC	Heating, Ventilation and Air Conditioning
HW	Hardware
ICD	Interface Control Document
ICT	Integrated Computing Team
IET	Integrated Engineering Team
IF	Intermediate Frequency
IFPS	IF Processor Subsystem
ITU	International Telecommunication Union
IVS	International VLBI Service
JAO	Joint ALMA Observatory
LAB	Laboratoire d'astrophysique de Bordeaux
LLC	Line Length Corrector
LMC	LLC Monitor & Control computer (also used for CLOA equipment)
LO	Local Oscillator
LPRA	LO Photonic Receiver Articles
LSB	Least Significant Bit or Lower Side-Band
LVDS	Low-Voltage Differential Signaling
M&C	Monitor and Control
MRR	Manufacturing Readiness Review
MTBF	Mean Time Between Failures
NAOJ	National Astronomical Observatory of Japan
NGAS	Next Generation Archiving System
NRAO	National Radio Astronomy Observatory
OOK	On Off Keying
OSF	Operations Support Facility
OSI	Open Systems Interconnection
OTN	Optical Transport Network
PA	Product Assurance

PDR	Preliminary Design Review
PDU	Power Distributor Unit (used to remotely power on/off/cycle bus master computers)
PI	Principle Investigator
PL	Pipeline
PLL	Phase Locked Loop
PLWG	Pipeline Working Group
PMD	Polarization Mode Dispersion
PPS	Pulse Per Second
PTP	Precision Time Protocol (IEEE-1588)
QA0	Quality Assurance Level 0
QA2	Quality Assurance Level 2
QSFP	Quad Small Form-factor Pluggable
RF	Radio Frequency
RFI	Radio Frequency Interference
SCWG	Signal Chain Requirements Working Group
SDH	Service Discovery Helper, or Synchronous Digital Hierarchy
SEU	Single Event Upset
S/FTP	Screened Fully shielded Twisted Pair
SKA	Square Kilometer Array
SMF	Single Mode Fiber
SMT	Surface Mount Technology
SOC	Scientific Organizing Committee
SONET	Synchronous Optical Networking
Spw	Spectral window
SQLD	Square Law Detector
SSR	Science Software Requirements (observing script software module)
STE	Standard Test Environment
SW	Software
TB	Technical Building
TE	Timing Event
UdB	Université de Bordeaux
UDP	User Datagram Protocol
USB	Upper Side-Band
VCO	Voltage Controlled Oscillator
VDIF	VLBI Data Interchange Format
WebSLT	Web Shift Log Tool
WCA	Warm Cartridge Assembly
WDM	Wavelength Division Multiplexing
WR	White Rabbit
WVR	Water Vapor Radiometer

A complete set of acronyms and abbreviations used in ALMA is maintained at the acronym list (https://wikis.alma.cl/bin/view/Main/AcronymsFinder) web page.

2 Technical Charges and their Analyses

This chapter addresses the individual technical charges as described in [AD2], section 2.2. Where applicable a review and analysis of requirements is provided for each charge. These requirements focus mainly at those at ALMA System Level 0 and recommendations are made that should be considered for an ALMA 2030 compliant version of [RD28]. Where appropriate requirements below Level 1 are addressed. The proposed ALMA 2030 requirements are summarized in tabular form in Chapter 6, Appendix A, and compared to current ALMA System Level 0 and Level 1 requirements [RD28] if existent.

2.1 Charge 1 – Software Operating Environment

Charge description [AD2]:
The working group shall suggest and present specifications for the software operating environment necessary to enable a new generation of backend, and data transmission systems, consistent with ALMA 2030 objectives to a System Requirements Working Group (to be established) and ICT for consideration.

The requirements considered for this charge are primarily the cross section between the SCWG sub-systems, back-end / DTS, and the ALMA Control Software. Roughly speaking this cross-section consists of two sets of requirements categories a) interface related and b) operational related.

In the category of interface requirements the Monitor & Control function will need attention. The current system widely uses a CAN-bus solution to interface with sub-systems. While this CAN-bus has proven to be a robust and proven solution for the current system it might not be the preferred choice for the future. The increased data rates needed for the future M&C functions might be beyond what can be offered by the CAN-bus, another issue is that CAN-bus standard employed by ALMA is no longer a widely supported standard and obsolescence will become an issue. With this in mind alternative solutions need to be investigated, an obvious choice might be Ethernet.

2.1.1 Communication interfaces with new equipment

At present the monitor & control interface to the majority of ALMA equipment is a Control Area Network (CAN) bus, a standard which was primarily developed for the automotive industry. This bus allows transmission at 1Mbit/s over a maximum cable length of 40m, but with multiple devices daisy-chained on a single cable. In ALMA an extra twisted pair is included in the CAN cables to provide the Timing Event (TE) synchronisation signal of 48ms period to each device. Although CAN has worked well for ALMA it has a number of drawbacks. The low bandwidth of 1Mbit/s can be a bottleneck when it is necessary to send or receive significant amounts of data from multiple devices on a bus. This has been particularly noticeable in the Baseline Correlator, but is also a potential issue in the antennas when high command or monitor rates are needed. The design of CAN and the short maximum cable length means that a bus master computer is needed quite locally to each group of devices, e.g., in each antenna. During the AIV period of ALMA the CAN cable lengths posed a real issue in the antennas, requiring a “cable trimming” campaign to improve reliability (e.g., AIV-4924), and the length limit restricted possibilities for lab test setups e.g., connecting devices in different rooms to an ABM. Software support for the CAN controllers in the bus master computers (ABMs, ARTM, LMCs, DMCs, CCC etc.) has been labour intensive, as ALMA has had to maintain custom drivers and port these with each change of operating system. The CAN standard, CAN-2.0, which ALMA adopted is also becoming obsolete and controller cards are becoming harder to find.

Ethernet is an example of a communication technology that could address these shortcomings. It has very widespread use and support across many sectors. There are various speed flavours offering from 2 to 5 orders of magnitude more bandwidth than CAN-2.0. Controllers are available for many devices and are often included on-board as standard. Drivers are generally well maintained by vendors and the open-source community, e.g., within the Linux kernel. Ethernet supports frame switching, which combined with supported line lengths of several tens of kilometers for some optical flavours, means that computers at OSF could directly communicate with devices in an antenna at AOS without needing an equivalent of the bus master computer in the antenna. For these reasons, Ethernet is currently the preferred option for data link layer.

If ethernet is adopted as data link layer, it will be necessary to specify which speed and physical layer to adopt, although this could potentially differ between devices in some cases. Choices for the connection from devices to switch include:

- 4 twisted pair 1000BASE-T; this is currently very common and inexpensive
- 1 twisted pair automotive ethernet e.g., 100BASE-T1, 1000BASE-T1
- Optical, now most commonly used at speeds of >=10Gb/s, typically using a pair of fibers

It should be noted that in all modern forms, ethernet uses a star topology, which would increase the total amount of cabling compared to the current daisy-chain CAN bus, although this is not expected to be a significant concern (e.g., a switch per rack could be used to concentrate traffic).

It is noted that when choosing the physical layer, RFI should be a consideration. Some copper ethernet options use frequencies up to several hundred MHz, for example, although RFI can be reduced with suitable high quality cabling (e.g., S/FTP).

2.1.1.1 Protocols

The ALMA monitoring and control requirements are only moderately time critical, with latencies of order of milliseconds generally being acceptable. For example, no fast feedback loops are closed using the ALMA M&C (such loops are generally handled within the devices themselves, although they may use similar communications technologies internally e.g., the drive servo loop of the DA antennas operates with 2ms period using ethernet). It is however important that the time is tracked accurately so that commands can be executed by devices simultaneously, and that the time at which a monitor occurred is known. Currently the simultaneous command execution is implemented using the 48ms period Timing Event (TE), with commands queued in devices during the current TE period and executed at the start of the next TE.

For communication, there is a convenience to using a reliable transport layer such as TCP over IP. TCP/IP has the advantage of being one of the most common protocols in networking, and it is easily managed in large networks, but it is noted that some optimisation of stack parameters may be required e.g., to quickly identify link failures. In ALMA we already use TCP/IP over ethernet for communication with several devices in the antennas and centrally (e.g., all the bus master computers, CVRs, PDUs, ACU ssh interface, Utility Modules, HVAC controller web interface). On top of the transport layer it may be desirable to adopt a standard machine-to-machine presentation/session layer such as OPC Unified Architecture (OPC UA), rather than designing a custom protocol for ALMA. OPC UA is an open, cross-platform standard with open-source implementations for C/C++ (as currently used by the ALMA control software for device level interactions), with interfaces to other common languages such as Python.

A major implication of the move from the ALMA CAN bus to ethernet will be the potential loss of the TE signal for time synchronisation (although the 125MHz reference distributed over separate coaxial cable could remain e.g., for high frequency clock generation and 180^o Walsh switching synchronisation). This is not necessarily a major concern, as network time protocols can achieve sufficient levels of time synchronisation accuracy. These also have the benefit of providing an absolute time rather than only a periodic signal that requires cycle counting to link to absolute time. Two main protocols for network time synchronisation exist: Network Time Protocol (NTP), and Precision Time Protocol (PTP, IEEE 1588-2008). NTP is generally implemented purely in software and places no specific requirements on network hardware such as switches. The synchronisation accuracy can typically be guaranteed to of order a millisecond, with values for closely connected hosts being potentially of order microseconds. PTP improves over NTP by requiring hardware timestamping support, and requiring dedicated support in network equipment such switches in order to account accurately for the delays they induce. The result is sub-microsecond synchronisation or potentially much better, and achievable in complex networks if all network equipment has support for it.

At this point it is hard to say whether PTP is necessary for ALMA time distribution, or if it may be possible to use NTP. Further study of this, potentially with testing with realistic network topologies, link lengths and network equipment (e.g., switches supporting PTP) would allow quantifying the actual accuracies and reliabilities obtainable with both options, and comparison to the jitter on the currently received TE. It is most likely that at least one option should be able to serve ALMA's device time synchronisation needs.

2.1.1.2 Transition and interoperability of new and legacy interfaces

For ALMA 2030 it is not necessary to replace all ALMA devices, as existing capabilities are sufficient. Example devices are the FLOOG, the Front End M&C and the ACUs. Although these may be upgraded for reasons of obsolescence management, we do not expect this would happen simultaneously, or in all cases prior to ALMA 2030 system rollout. Therefore, there will be a period, likely of many years, in which a mix of new ethernet devices and legacy CAN+TE devices will need to coexist and interoperate. This will need to be planned for. Potentially the new ethernet devices could, in the medium term, be commanded from the existing bus master computers (which have gigabit ethernet interfaces) along with the CAN devices. However, obsolescence management of the bus master computers themselves may drive a different solution, in which the M&C of the ALMA control software moves entirely to a central location, with lightweight dedicated ethernet to CAN bridges (which would not need software updates in line with the ALMA software) used in place of the existing full bus master computers. This option is being studied by the Ethernet to CAN (E2C) project at NRAO (https://confluence.alma.cl/pages/viewpage.action?spaceKey=ICTCORR&title=ALMA+Sustainability+Presentation).

Another approach that could be considered is to replace the AMBSII CAN communication boards in legacy devices by electrically and mechanically compatible boards with ethernet interfaces. However, in addition to the hardware development, for each type of device this would entail developing new firmware and extensive testing and commissioning efforts to ensure continued reliable operation. Thus, this approach is not currently recommended.

2.2 Impacted software components

Based on the current ALMA software, we can highlight areas of the software subsystems impacted by the signal chain upgrade and ALMA 2030 more widely.

2.2.1 Common software to online and offline

The ALMA Project Data Model (APDM), which is used to define observing projects and their Scheduling Blocks will need updated to support the ALMA 2030 frequency setups and correlator configurations in the spectral specifications in Scheduling Blocks and associated Science Goals. This will have wide-ranging impact as many software components online and offline interpret these parts of the APDM. For example, the Observing Tool, Scheduling, SSR, the control and correlator software access it

The ALMA Science Data Model, which defines how data is recorded by the observatory, will potentially only require a minor update to add a new correlator type. The ASDM is quite flexible with regard to spectral setups, for example supporting recording of an arbitrary number of LO conversions in the metadata. However, the current software implementation of the ASDM has known performance scalability issues that will likely need to be addressed for ALMA 2030, and would improve observing and data processing efficiency. The effects are likely to be most acute for spectral calibration tables (e.g., CalAtmosphere, SysCal, CalBandpass) which will increase in size proportionally to the number of channels output by the correlator. The binary data storage in the ASDM should also be reviewed for performance scalability for higher output data sizes. No specific problem is foreseen with scalability at this stage, but perhaps it could be optimised for higher read/write performance. Changes to the API for the ASDM software would impact several subsystems online and offline.

There will likely be a need for TelCal and offline software to be able to identify receiver properties on a per-antenna basis during receiver band upgrade programmes (which may take 3 years), during which a mix of old and new receivers may be used in an array. This could potentially be achieved in the ASDM by identifying the receiver type per antenna, or conveying the necessary information such as nominal sideband gains and IF frequency ranges per antenna.

In general, all software enumerations relating to the signal chain will need reviewed and updated if necessary.

2.2.2 Online subsystems (excluding correlator): Control, SSR, and TelCal

In the online software, modifications will be required at various levels due to the close and complex interaction with the hardware. It is assumed that a new correlator software subsystem will be written to support the next generation correlator, and this is not considered here. Looking at the current implementations, we can identify at least the following areas that will be significantly impacted by the signal chain upgrade:

1. Low level communications interfaces e.g., implementation of the chosen ethernet-based communication protocol. Depending on architecture this may include timing, e.g., like the teHandler and ArrayTime in the current system
2. Control software device components (like drivers) to monitor and control each of the new devices will need to be written. This would include defining TMCDB configuration schemas for the devices.
3. New user interfaces to monitor and control devices e.g., like the CorrGUI, total power GUI and array status GUIs. The strong uptake of python in engineering lab applications in recent years may make ALMA 2030 an opportunity to reduce duplication and bifurcation between ALMA software GUIs and GUIs used by engineering teams that are presently written in LabView.
4. Interfaces between the device components and the observing modes (LocalOscillator, InterferometryController etc.)
5. Observing modes support for the new devices e.g. for tuning, delay tracking and controlling Walsh switching
6. The LO solutions software which converts desired sky frequencies into LO frequencies will need to be replaced by an equivalent ALMA 2030 version. This will likely be much simpler due to no longer having to account for a second LO conversion and the discontinuous tuning coverage of the current LO2s. Due to the wide IF frequency range it is expected to be beneficial to allow having one IF sideband extend beyond the nominal RF range of the band (with a suitable LO1 tuning range of the receiver to support this), in order that certain spectral line combinations can be observed simultaneously within the nominal RF frequency range without some falling into the frequency gap between sidebands. This capability is particularly relevant to the lower frequency end of an upgraded Band 6 receiver to be able to observe multiple CO isotopologues simultaneously. In this situation, the intention would be that correlator spectral windows are only placed within the nominal RF range, i.e., that the part of the IF extending beyond the RF band edge not have science data recorded for it.
7. The TotalPowerProcessor, which is responsible for recording data from the baseband power detectors in the IF processors into ASDM binary files, will need to be replaced or largely re-written to support ALMA 2030 total power detectors (which may be in the digitiser or IF Switch modules, see section 2.3.4)
8. The Delay Server and the delay event structure will need changes to support ALMA 2030 delay correction architecture (section 2.7.4). It is recommended to consider only sending the total, unquantised, delays for each antenna, rather than the quantised values to be applied by each hardware device. The software controlling each device in the delay correction chain can compute the instrumental values in a consistent way. This will significantly reduce the required data rates in long baseline configurations and will be particularly advantageous for extended baselines envisaged for ALMA2030.
9. New instrument optimisations and calibrations may need to be implemented and integrated into the observing sequences, for example in the current system, the IF and baseband power optimisations and the correlator calibrations. It might be that periodic calibrations are required for the digitisers.
10. The ALMA 2030 implementations could also be an opportunity to support instrument calibrations that are performed outside normal observations, e.g., digitiser level optimisations and power detector offset measurements, into the ALMA software so they can be efficiently performed on a parallel/array basis.

11. Observing scripts will need to be adapted to support the changed functionality and interfaces. The APDM changes to the frequency setups and correlator configurations will be particularly relevant, as almost all observing scripts generate or interact with these structures. The changes to instrument calibrations (see previous point) may need to be managed from the observing scripts. Any changes to higher level (e.g., astronomical) calibration strategies will also need to be implemented in the observing scripts.
12. Scalability of interfaces between components that convey any spectral results will need to be reviewed. For example, the interface between TelCal and DataCapturer. This review may also address existing general performance issues with moderately large data volumes e.g. transferring antenna pointing data for long subscans between the observing modes and DataCapturer.
13. Scalability of the Bulk Data system for transporting the data from correlator and other producers to receivers including the archive and TelCal should be reviewed. Tests a few years ago already indicated that within the STE network using 10--40GB/s links it was feasible to operate at 300MB/s, and with further upgrades this will presumably increase further. Whilst this is therefore not a major concern, the scalability should be quantified under relevant scenarios.
14. The flow of data to the archive should be assessed for scalability issues. An upgrade of NGAS to a version which has been optimised by developers at the International Centre for Radio Astronomy Research (ICRAR) is already underway, with current planning expecting deployment at JAO to be completed by Feb 2022[1]. Tests have shown that this will improve performance substantially both for data ingestion and retrieval. Network and computer hardware for the NGAS front-ends at OSF and their connection to the STE can also be upgraded, which may happen naturally as hardware falls out of warranty and is replaced (nominally every 5 years). For reference, with the current (now referred to as “legacy”) NGAS, the effective ingestion speed from the STE to NGAS FE over a 10Gb/s link is about 170MB/s. One point that may require attention in computing hardware is the speed of the disk cache in the STE, where BDFs are staged between being received over the Bulk Data transport within the STE and being sent to the NGAS FE. This disk area will need to be able to sustain the maximum correlator data rate for writing while simultaneously being read. This is not a challenging requirement for modern high performance solid state disks, but it will need to be set as a requirement.
15. Although not strictly related to the hardware upgrade, with the correlator software redesign it is suggested to investigate having a single central component record the WVR data for the ASDM. At present this is duplicated in each correlator subsystem. The means of distributing the WVR data from the antennas to the component responsible for recording them and to the correlators (now only for phased array operation) may also warrant review to maximise reliability.
16. The TelCal subsystem will need modifications due to the change of frequency setup, and in particular the removal of the second LO conversion. A small number of assumed parameters for each receiver band will need updated as new receivers are added.
17. TelCal may need to work on spectral data for calibrations that currently work with low data rate channel average data from the correlators. This is due to the greater prevalence of atmospheric spectral lines within the broad basebands requiring a weighted averaging. This will require implementation work, but will also significantly increase processing

---

[1] https://confluence.alma.cl/pages/viewpage.action?spaceKey=ICTARCH&title=NGAS+GitHub+Migration+Project+Plan

requirements for time-critical (near real time) calibrations such as pointing and focus. The result will be achieving a maximal signal to noise, and allowing fainter calibration sources than with the current lower bandwidth system.

18. The ATM library which TelCal relies on for atmosphere spectral modelling may require performance improvements to allow scaling to larger numbers of channels and the increased bandwidths.
19. In general, in view of scalability the architecture of TelCal for processing of computationally and I/O heavy calibrations may need to be reconsidered. At present some calibrations such as bandpass and atmosphere with many antennas and the current numbers of spectral channels are a stretch for the current architecture even on a dedicated high-performance computer. This also relates to the ASDM implementation performance mentioned in the previous section, as fast and multi-threaded access to data will likely be needed.

2.2.3 Offline components: Observing Tool, Sensitivity Calculator, Pipeline, Archive

2.2.3.1 Observing Tool

Many aspects of the ALMA 2030 upgrade will need to be reflected in the Observing Tool (OT) which presents the telescope capabilities to the user and generates Scheduling Blocks (SBs). For example, the increase in bandwidth of the new digitizer IF basebands, and the change in number of configurable basebands will need to be encoded in the OT logic and graphical displays. New rules for how spectral windows can be defined and distributed in the new correlator will need to be understood, coded, and documented for users and observatory and ARC staff. Similarly, the changes in receiver band IF ranges, receiver type (2SB vs. DSB), and any small increase in RF band ranges (such as under consideration for the upper and lower ends of Band 6) will need to be accounted. As described in section 2.1.3.6, the ability for one sideband to extend beyond the nominal RF range will need to be accommodated, but with no spectral windows allowed beyond the RF range. The choice of the “continuum default” tuning will also need to be reoptimized by Science for each receiver band that is upgraded to provide wider IF ranges. Because the OT must continue to function for the current ALMA hardware configuration, presumably it will need to have a mechanism in which it can be opened in an "ALMA 2030 mode” for testing and commissioning purposes. This mode will need to include any special setup commands for the new correlator in the SBs that it generates, while maintaining the existing IF range limitations of the legacy receivers.

2.2.3.2 ALMA Sensitivity Calculator

The OT also relies on the ALMA Sensitivity Calculator (ASC) to compute required observing times. This calculator will need to be updated to reflect new digital system efficiency (including contributions from the digitizer, DTS, and correlator), receiver temperatures, and available bandwidth. While the web-based GUI version of the ASC allows the input of arbitrarily large (or small) bandwidths, it makes no attempt to account for the changes in atmospheric performance across wide IF bands. Thus, the continuum sensitivity estimates based solely on a centre frequency and bandwidth will become less realistic unless this aspect is accounted for in the new ALMA 2030 version.

2.2.3.3 Pipeline

The impact of ALMA 2030 on the Pipeline (PL) will be most significant in terms of the large increase in number channels to be calibrated and imaged. The footprint of datasets on disk and in memory will increase accordingly. PL processing times will likely increase substantially, at least until computer hardware and disk I/O performance improve enough to match the large step upward in ALMA 2030 data sizes. Also, the larger fractional bandwidth of the observations will impact the heuristics used by the pipeline. For example, the use of multiple Taylor terms in multifrequency synthesis (mfs) imaging is needed to properly account for the frequency-dependent variation in continuum flux density (spectral index) and primary beam-size. Its use will become more commonplace than at present, in which it is only triggered in the lower bands where the fractional bandwidths can exceed 10%. With the larger variation of system temperature across the wider IFs, the use of spectral weights will become much more important to achieve optimal calibration and imaging. Currently, the weights are scalar values per spectral window (spw), so using vectorized weights will further increase the PL processing time and the storage footprint of the processed datasets. A related point is that the temporal gain calibration methods, including the WVR corrections, currently assume a non-dispersive atmosphere. This assumption breaks down near strong atmospheric lines, so some improvement in calibration might be gained by accounting for this effect using the atmospheric model.

Another category of items will have modest impacts on the PL. For example, the improvement in digital efficiency will require an update in that term in the sensitivity equation in the pipeline, which is used to determine when low signal-to-noise heuristics need to be invoked during calibration. Also, if the wider IF bandwidth is affected by system-generated RFI, such as birdies from the LO1 generation, then a new spectral flagging heuristic may need to be added to the deterministic flagging stage of the calibration recipe. Changes in receiver type (DSB to 2SB) will likely require minor PL changes, as there may be some areas of the code where DSB is assumed for Bands 9 and 10 rather than consulting the receiver type enumeration in the ASDM.

Fortunately, some aspects of the ALMA 2030 hardware changes will have little to no impact on the PL. For example, the reduction in number of basebands should have no impact because the PL already supports projects with fewer than 4 basebands.

On a positive note, the general increase in continuum bandwidth of the datasets means that self-calibration will be possible on a greater fraction of science targets, leading to better data products for the PI and the Archive. At the same time, the higher sensitivity means that more science target images will become dynamic range limited, and thus the ALMA project will need to rely on self-calibration to meet the PI requested sensitivity in order to pass QA2. Adding a self-calibration capability is in the near-term plans of the PL working group (PLWG), with some initial necessary framework changes underway for the Cycle 9 pipeline. The initial capability will hopefully be implemented in the next few years, in time for it to be available when the ALMA 2030 system is deployed.

2.2.3.4 Archive

The increase in size of the raw and processed data products will similarly impact the Archive storage and data transfer rate requirements. If problems arise with scaling the current infrastructure, the usage of cloud storage may help alleviate the load, particularly at the various ARCs. Other facilities that will come online in the 2030s are introducing a science platform, such as the Rubin Science Platform (https://nb.lsst.io), which may be worth considering for ALMA. The CARTA viewer under development by CASA represents a step in this direction.

2.2.3.5 Calibrator database and flux density service

Presently, Bands 3 and 7 are the bands most often used to monitor flux densities of the two dozen quasar grid calibrators for establishing the flux scale of ALMA science data. When either of those bands is upgraded to wider IF ranges, or if Band 2 is used in the future instead of the current Band 3, the fractional bandwidth of the measurement will increase as will the separation of the mean frequency of the two sidebands. Populating the catalogue with multiple flux density values per sideband and fitting for the spectral index within the lower frequency band alone may offer greater accuracy in flux density values than the current inter-band method delivers to the pipeline queries.

2.2.3.6 Scheduler

The Scheduler software uses some internal tables containing typical system temperature values in order to estimate an *a priori* execution fraction. If new receiver bands have significantly different performance, these tables will need to be updated.

2.2.3.7 CASA

Similar to the Scheduler, the simulator module of CASA contains the receiver temperature and RF band range specifications for each band. These will need to be updated on a band-by-band basis. Also, the MeasurementSet (ms) metadata tool of CASA contains a method used by the Pipeline called “almaspws”, which will need to be updated because it contains hardcoded values and logic for what constitutes a TDM spectral window vs. FDM spectral window based on the bandwidth (2.0 GHz) and number of channels (64, 128, or 256). Since there will be no equivalent distinction with the new digital datastream, we will need to define a new ALMA2030 spectral window type in this function.

2.2.3.8 Other subsystems

Other offline subsystems will likely need minor updates to be able to distinguish between the baseline correlator and next generation correlator when querying databases or labelling retrieved results. Examples include AQUA, QA0, ProjectTracker, and WebSLT.

2.2.3.9 Documentation

For all of the aforementioned subsystems, the documentation will need to be updated to reflect the required changes that are implemented for ALMA 2030.

2.3 Charge 2 – Backend

Charge description [AD2]:
The working group shall develop and present specifications for a new generation of backend systems, consistent with ALMA 2030 objectives, and with the specifications proposed by the FEWG.

As defined by the ALMA Product Tree [RD25] the following Backend products in operational use in the ALMA system architecture at Level 1 are to be considered:

52 - IF Processor Sub-subsystem (IFPS)
53 - Data Transmission Sub-subsystem (DTS)
54 - Fiber Optic Transmission Sub-subsystem (FOTS)
55 - LO & Time Reference Sub-subsystem (LOT)
56 - Photonic 1st LO Reference Sub-subsystem (PLO)
57 - BE Miscellaneous Equipment

Given SCWG Charge 3 the BE products 53 - Data Transmission Sub-subsystem (DTS), and 54 - Fiber Optic Transmission Sub-subsystem (FOTS), are addressed in section 2.4 of this document.
BE products 55 - LO & Time Reference Sub-subsystem (LOT) and 56 - Photonic 1st LO Reference Sub-subsystem (PLO) are subject of SCWG Charge 8 and addressed in section 2.9.
BE product 57 - BE Miscellaneous Equipment primarily includes backend housing, power supplies, and cabling. The specifications for this product only need to be considered at a more advanced design level and are currently outside the scope of this document.

2.3.1 IF Processor Sub-subsystem (IFPS)

BE product 52 - IF Processor Sub-subsystem (IFPS) is the main topic of this section. For this purpose we adopt the signal chain architecture as recommended by the ALMA Frontend & Digitizer Specification Working Group in [RD2].

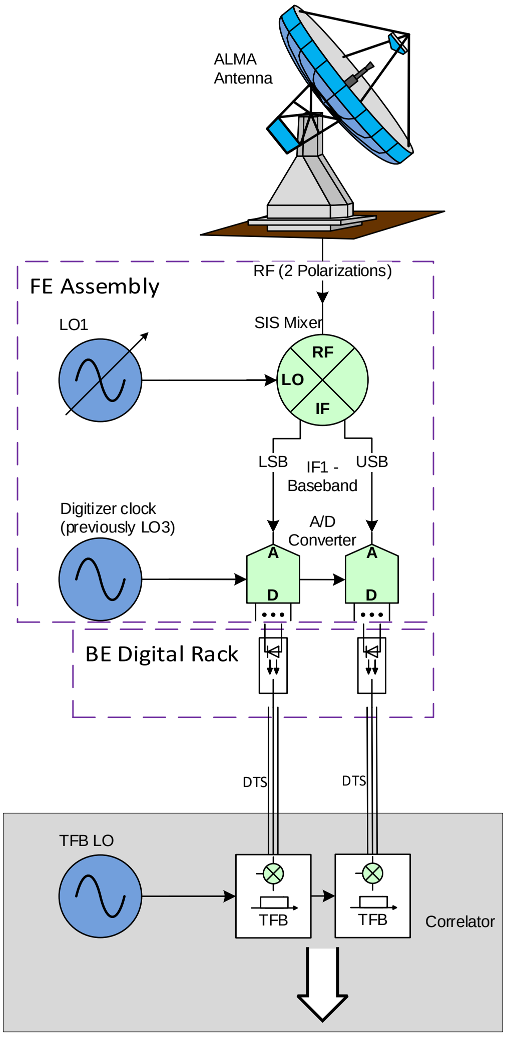


Figure 1 Summary block diagram of ALMA 2030 signal path and LO with a notional correlator including tunable filter banks as a first "F" coarse channelization (section 2.5.1)

As is depicted in Figure 1 the proposed signal chain architecture, removing the second heterodyning stage, greatly simplifies the IFPS. The SCWG advocates that the new digitizers are co-located inside the existing FE-Assembly, possibly integrated with a new, wideband, IF switch (current product item FEND-40.08.01.00 [RD25]), outfitted with wider bandwidth (20 GHz) attenuators and square law power detectors (SQLD), making the current IF_2 products inside the BE Analog Rack, mounted inside the Antenna Receiver cabin, completely obsolete. The main advantage of mounting the new digitizers in the FE-Assembly is that the long, lossy, and expensive coaxial cables (which degrade bandpass flatness) transporting the IF signals between FE-Assembly and BE Analog Rack can be avoided. The digitized signals can be transported by a dedicated, optical link, e.g. using Samtec FireFly technology (https://www.samtec.com/optics/optical-cable/mid-board/firefly) [RD27], from the FE-Assembly to the Digital Backend Rack where formatting and possibly signal processing is applied before the data stream is sent via the DTS from each antenna to the central correlator.

Assuming the described new IF signal chain architecture there is no IF Processor Sub-subsystem (IFPS / product item FEND-52.00.00.00 [RD25]) present anymore. As such no corresponding

IFPS product requirements need to be defined, however some of the functions currently implemented in the IFPS need to be allocated to other subsystems.

2.3.2 IF attenuators

The current ALMA system architecture enables the adjustment of the signal level applied to each digitizer, independent for each IF channel, with a resolution of 0.5 dB. This resolution is provided across a total range of 46.5 dB by a combination of digital step attenuators inside the Front End IF Switch Module, having a resolution of 1 dB [RD29], and the Back End IF Downconverters, providing a resolution down to 0.5 dB [RD30]. It is foreseen that a minimum resolution of 0.5 dB step size is implemented in an upgraded IF switch (current product item FEND-40.08.01.00 [RD25]). This requirement shall apply to the whole IF band digitized.

The total required IF attenuation range shall be reassessed taking into account the foreseen variations in sky and astronomical source variations, including those for solar observations, and gain variations in the analogue signal chain. These analogue gain variations will consist of contributions from the FE sub-system and the digitizer input circuitry.

The current IF attenuation range is distributed between IF switch (product item FEND-40.08.01.00 [RD25]), being nominally 15 dB, and the IF Down-converter (product item FEND-56.02.00.00 [RD25]), being nominally 31.5 dB.

2.3.3 Analogue power detectors

Following the System-Level Technical Requirements [RD28] the current system foresees analogue power detectors for both first IF (Req. # 513) as well as for each baseband in the second IF (Req. # 511). Both types of power detectors are implemented in the Analog Backend IF Downconverter (product item FEND-52.06.00.00 [RD25]). The conversion of the analogue detector signals to digital data is performed by the Total Power Digitizer & Monitor Control (product item FEND-52.07.00.00 [RD25]).

Since it is not foreseen in the ALMA 2030 architecture to retain the IF Processor Sub-subsystem (IFPS / product item FEND-52.00.00.00 [RD25]) the analogue power detectors need to be implemented in another sub-system. It is advocated that these detector functions, including the digitization, are implemented as part of a new, wideband, IF switch in the FE-Assembly.

Due to the absence of the second down conversion to baseband in the ALMA 2030 architecture, the baseband detectors (Req. # 511) should be preceded by an analogue bandpass filter to define the broadband, e.g. 4 – 20 GHz, first IF signal path that forms the input to these detectors. The exact frequency response of these bandpass filters has to be determined.

The sampling rate requirement, 2 kHz, for both type of analogue power detectors (Req. # 512) remains unchanged.

Requirements for the broadband detectors (Req. # 513) will change for ALMA 2030. The detected bandwidth of currently 8 GHz will increase to the value adopted following the recommendation from the FE/Digitizer WG [RD2], likely 16 GHz.

Another amendment to the requirements for the broadband detectors comes from the fact that their actual use is not limited to engineering monitoring, as specified in Req. # 513, purposes only. Current operations uses these broadband detectors also for single dish, total power, astronomical observations specifically of the sun. With this astronomical use in mind and to allow for a more meaningful use in engineering monitoring, it is recommended that the new broadband detectors provide a calibratable scale. The required accuracy of this level scale is to be determined in consultation with the astronomical user community and JAO operations. It is expected that for the purpose of this calibratable level scale requirement a zeroing feature and potentially a calibrated noise source for detector gain calibration need to be implemented in the new IF switch/Digitizer assembly.

2.3.4 Strawman IF Switch

As argued in the previous sections a new IF switch assembly with integrated Digitizer and analogue power detectors located inside the FE Assembly is advocated.

The current IF Switch Assembly consists of four IF Switch modules, one per polarization and sideband, and a separate M&C Module which are located in an Eurocard rack (Figure 2). The essential signal chain elements of a single IF Switch module are presented as a block diagram in Figure 3.

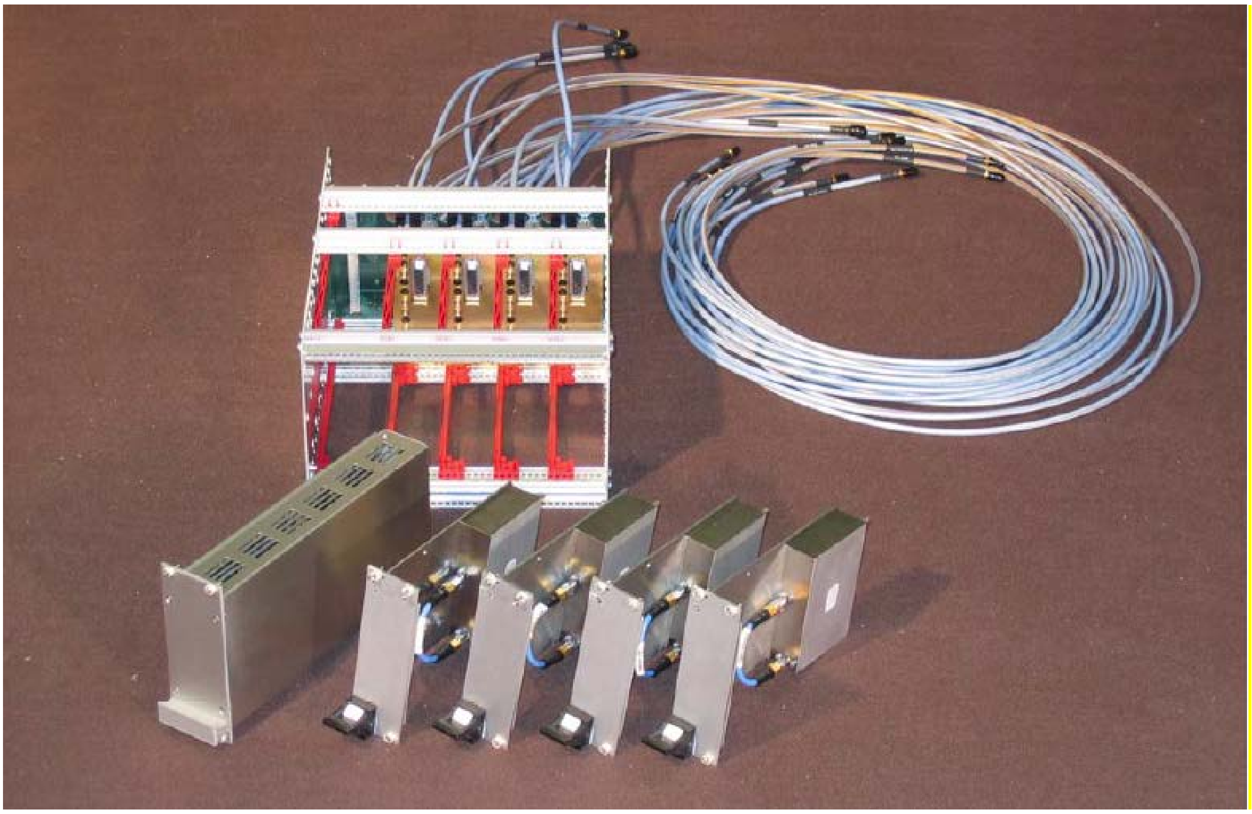


Figure 2 Complete IF Switch Assembly with its M&C module and four IF Switch modules removed from the rack

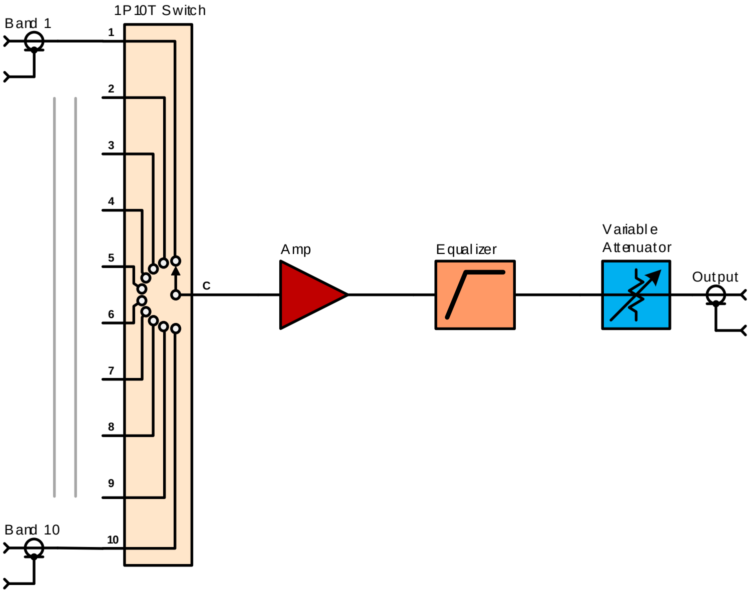


Figure 3 Simplified block diagram of the current IF Switch Module

Figure 4 below provides a strawman block diagram for a new IF Switch module fulfilling the requirements of the ALMA 2030 system architecture and to be considered as a replacement for the current unit.

This strawman concept provides the functionality described in sections 2.3.1 - 2.3.3 including the availability of an analogue, legacy, output to feed the current analogue Back-end rack as is desirable during the transition phase from current system to ALMA 2030.

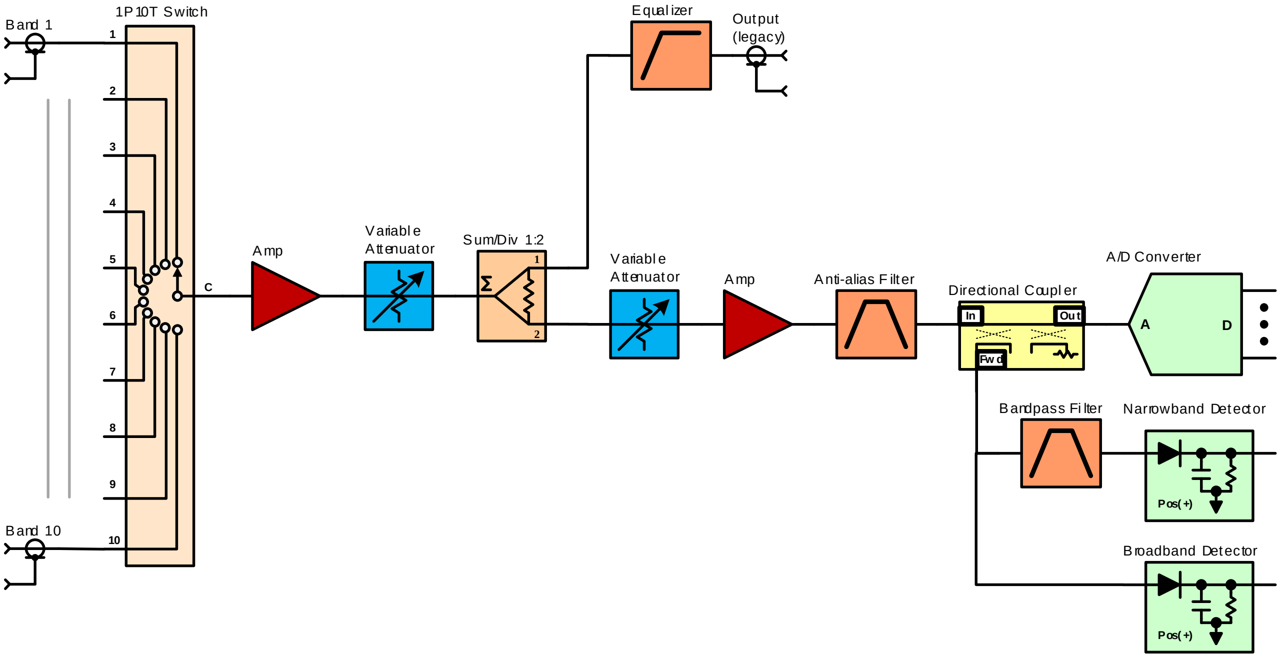


Figure 4 Simplified block diagram strawman ALMA 2030 IF Switch Module

It is obvious that space allocation for the new IF Switch module is restricted and not much more compared to what is currently available for the IF Switch Assembly. A high density PCB design using miniaturized surface-mounted components with a high level of feature integration as commonly available nowadays should enable this. Careful thermal analysis of the module will be mandatory for a reliable design capable of operating at the AOS altitude.

2.4 Charge 3 – Data Transmission System

Charge description [AD2]:
The working group shall develop and present specifications for a new generation of data transmission system, consistent with ALMA 2030 objectives, and with the specifications proposed by the FEWG and CorrWG.

2.4.1 Assumptions & Conditions

In an effort to frame the recommendations, the following technical assumptions were made:

- The Effective Number of Bits (ENOB) will be at least 5, if not 6. For the purposes of this document, a (consensus) number of bits of 6 will be used for most specifications and calculations. 8 bits may be referenced, as it represents the stretch goal (see Section 2.4.2) and an upper limit for the required Data Transmission Rate. If fewer bits are ultimately required, this can only decrease the required total transmission bandwidth.
- The available space in the Digital rack will be at least the same as the current DTX system that makes use of the GenV RFI enclosures, but no less. The Analog Rack systems (source of the 125 MHz and 48 ms TE for the DGCK digitizer clock) are not expected to change, and the FE Receiver Electronics Chassis space was not considered.
- New power requirements must not affect Antenna Cabin temperature stability (to avoid impact on the 1st LO phase drift)
- The ALMA 2030 document focuses on “baselines”, which are a Correlator/mathematical Antenna-to-Antenna construct not relevant to Engineering concerns. In this document, distances will relate to Antenna Pad-to-AOS Technical Building (AOS-TB), and AOS-TB -to-Operations Support Facility (OSF) building, where actual cabling must be available and signals must travel to their destinations with sufficient strength.
- The new Correlator will be located at the OSF, and ALMA 2030 [AD1] expects the maximum baseline length to at least double (2x) if not triple (3x), which could imply a pad to AOS building distance of 45 km, which must now be added to the AOS to OSF distance (29 km) for a total of 74 km. For this document, a distance requirement of 75 km will be used, to provide for adequate margins.
- The simplest architecture is aimed for, which eliminates any type of 3R (Receive, Regenerate, Retransmit) type pit stop of the data in the AOS building, and focuses on a direct antenna pad to OSF link, unless data “time-stamping issues” are encountered.

2.4.2 Bandwidth requirements

Given the technical requirement goals laid out in [RD1] and [RD2] for a 6 bit or more, Double Side Band (DSB), dual polarization receiver at 16 GHz bandwidth per pol, the maximum (peak) required bandwidth (maximum instantaneous data rate) to be transmitted to the correlator can be approximated as:

Option 1) [**preferred by RD02 and this SCWG document**] with no second down-conversion (IF range = 4-20 GHz):

# of bits x 2 Sidebands x 2 polarizations x 20 GHz x 2 (Nyquist) = 6x2x2x20x2 = 960 Gb/s of data

Option 2) with bandwidth extracted via DSP at the antenna (effective IF range = 0-16 GHz):

# of bits x 2 Sidebands x 2 polarizations x 16 GHz x 2 (Nyquist) 6x2x2x16x2 = 768 Gb/s of data

These rates are just for the actual raw data, and do not include any of the required overheads or data error correction ("Forward Error Correction, or FEC). A realistic placeholder target rate of 1.2 Tb/s (1200 Gb/s) for option 1 and 800 Gb/s for option 2 will be used.

(Note: if we use the stretch goal ENOB of 8, the max instantaneous data rate becomes 1,280 Gb/S, resulting in a target rate of 1.6 Tb/s)

2.4.3 Data Transmission System

At time of writing, the currently installed Amplitude-Modulated (OOK: On-OFF Keying) UDP format data transmission system cannot transmit that amount of data over a single fiber over the required distance. Even upgrading to higher bandwidth OOK units (40 Gb/s) may still not meet the distance requirements, as Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) will require extra mitigation steps. But for the sake of thoroughness, a system designed for option 1 means each antenna would need:

30 Tx + DWDM MUX + Inline EDFA + Dispersion Compensation Fiber + DEDICATED FIBER to OSF

Such DWDM systems can reliably transmit up to 256 channels per fiber, but ALMA 2030 goals require 66 x 30 = 1,980 channels (up to 2,400 channels if we consider 80 antennas). An upgraded ALMA must either provide an extra 80 fiber cable to the OSF, or dedicate each antenna to a specific existing fiber (see next section below) AND to a specific set of Tx lasers that can no longer be interchangeable from one to the other (and thus ALMA will have to procure a large number of unique spares) unless tunable lasers are used, and assign a unique fiber to each antenna grouping, until all channels are coupled.

Moreover, the 75 km span means the fiber can only be the Single Mode Fiber (SMF) type used in Long Haul type applications, and cannot accommodate any transmitter operating below 1.2 microns (cut-off wavelength).

Based on these requirements, it is our recommendation that the most straightforward commercially available solution is to be found in the area of "Data Center Interconnects" or DCI, tasked with moving vast amounts of data from ("cloud") server farm to server farm (Facebook, Google, or Amazon, for example, being the main drivers). The current DCI industry approved max span figure is 80 km, which lines up with the assumption listed in 2.4.1.

As explained above, to mitigate the long-range effects of pulse spreading due to Chromatic Dispersion and Polarization Mode Dispersion, the current Direct Detection Amplitude Modulation (OOK) method widely used (or that had been proposed at an earlier time) in 40 Gb/s (or less) systems like ALMA is being replaced by Coherent modulation (ex: QPSK: Quadrature Phase Shift Keying). High performance, long range 100 Gb/s, 200 Gb/s, and 400 Gb/s are all Coherent type formats.

The recommended data transmission hardware family that can meet the target specs is the current industry-developed family of 400G CFP2/4 or QSFP-DD Digital Coherent Optics Transceivers. This would allow the entire data stream from each antenna to be carried by a small number (two, three, or four) 400Gb/s systems.

An independently derived, recently released report [RD27] has come to a very similar conclusion and recommendation.

While expensive as currently offered in the early 2020s, they should be much more affordable by the middle of this decade, based mostly on projected DCI volumes (which have already tripled since 2016), with a target value of US$1/Gb being envisioned. A recently contacted large US based commercial vendor has proposed a QSFP-DD solution that would cost approximately US$ 40,000 for the 1.2 Tb/s Transmit/Receive equipment required by each antenna, for a total of US$ 3M to outfit all 66 telescopes (plus spares), or $33.3/Gb.

Moreover, the two major Standards bodies (ITU and IEEE) are actively writing industry-wide standards for 400 GbE solutions, meaning a uniform offering by multiple vendors, which will lead to competitive costs, plentiful sparing and long-term availability. This progress is in line with the Charge 5 recommendation below.

This generation is also currently available as a Dense Wavelength Division Multiplexing (DWDM) solution, in either fixed or tuneable wavelength format; ALMA 2030 would be able to carefully select fixed wavelengths and assign them to a specific antenna, making multilane data streams in one fiber possible (see caveat above), or procure only tuneable laser models, thus reducing the total amount of necessary spares, while still only requiring 3 x 400G units to cover the target data rate.

And while this type of transmission hardware is more DSP/FPGA intensive than ALMA’s current system (to encode not only the raw data but add Overhead and Forward Error Correction), the push is to offer an encoding + transmission (integrated DSP + Transceiver) solution that requires less than 20W at the Transmit end, for a projected 60 to 80 W per antenna power consumption @ 1.2 Tb/s.

A sample COTS 1.6 Tb/s chassis capable of hosting 400 GbE modules (large slots) is shown below:

Figure 5: COTS 1.6 Tb/s chassis capable of hosting 400 GbE modules

While compact and feature rich, care will have to be taken nonetheless with RFI shielding, cooling fans and related issues, leading to a certain amount of customization. Some vendors are willing to sell unpackaged solutions as individual components, allowing ALMA to reuse the same GenV enclosures currently housing the DTX system. Once again, this solution may offer the customization flexibility often required by ALMA.

Additionally, current Coherent transmission systems at 400G have a point-to-point power budget limited to 40 km, requiring either a booster, a preamp, or an inline EDFA to reach the required 80 km. Thus, any pad located outside of a 5 to 7 km radius (because of necessary operational and EOL margins) will have to be connected to a WDM optical amplifier (or multiple ones if the upgraded system is not DWDM based) before being sent down to the OSF, either in the antenna DTX module, just before the DRX module at the Correlator, or midway in the AOS building:

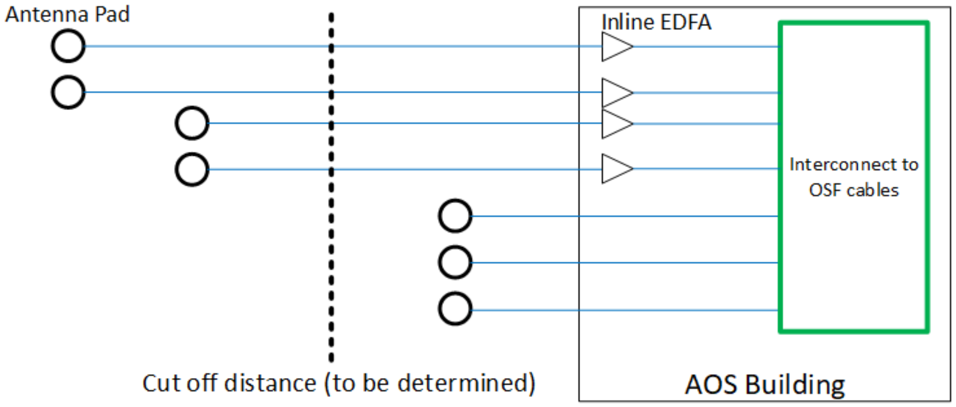


Figure 6 Fiber connections from antennas to AOS building; longer fibers may need inline amplifiers

This could mean for example that all the ACA antennas would be exempt, and the overall solution is relatively simple and straightforward. The Hardware in the Loop (HiL) project is already installing EDFAs in the patch panel room of the AOS, so a similar solution can be adopted here.

Again, this is based on 2020/2021 commercially available solutions. Price and performance may improve in the next few years, and commercial vendors have indicated willingness to customize solutions to fit ALMA's needs.

Note that the currently deployed DTS system and its designated fiber cannot be reused or repurposed in any meaningful way, especially if there is to be a parallel deployment of the baseline and upgraded systems without interruptions to Science Operations.

2.4.4 Existing and available fibers versus new cables, antenna pad to OSF

(with contributions from Giorgio Filippi @ ESO)

The current ALMA system has the entire data stream from each antenna travel through 1 of the 8 fibers in the cable going to each of the 192 pads (i.e., 192 cables). And out of the total, 4 are in use (LO, DTS, and 2 for Monitor & Control), and 4 are currently designated as spares (drawn in grey on the ALMA block diagram: [AD4]). This offers the possibility of having up to 5 fibers (current DTS fiber + all 4 spares) available to the (upgraded) DTS system, going from each pad to the AOS building. However, limiting the new DTS to 4 (or fewer) fibers would enable parallel deployment, and minimize science down time (see section 3.2). Also, it should be kept in mind that the 4 fibers designated as spares are the lowest performing fibers in terms of loss, and in some cases, they may be unusable without repair [See appendix A.4 of RD1]. As a result, a new DTS system using significantly fewer than 4 fibers is desirable in order to maintain at least 1 functional spare fiber.

If the Correlator is located at the OSF, then the raw data from each antenna must be transported over the additional 29 km down to the OSF. There is an existing 48 fiber cable (containing 4 x 12 fiber tubes, with between 18 and 22 unused fibers available, possibly a few more with proper repurposing) installed between the AOS and OSF buildings, added on as part of the power cable installation. It is a “modern” G.652 compliant single mode fiber with low CD and PMD values (less than 0.06 ps/sqrt km). However, it has already been broken and repaired more than once over the past years, and its current performance and suitability for ALMA 2030 would have to be confirmed as adequate. The technical solution offered in Section 2.4.3 relies on a fiber with an average attenuation of less than 0.25 dB/km to achieve an error free, reliable transmission.

The technical consensus recommendation then is to install a new, dedicated, high fiber count (> 160 fibers) cable between the AOS and OSF, which provides a dedicated signal path between each antenna and the Correlator (as is currently the case), would allow redundancy, and anticipate possible future upgrade needs.

From an operational stand point, it also prevents multiple antenna data streams from failing simultaneously, should a fiber carrying multiplexed data encounter a problem (incorrect connection at AOS, damaged fiber cable or connector at fanout points, …), and not hinder or constrain already ongoing projects using the cable (such as Hardware in the Loop).

A quick survey study was carried out for the benefit of the Working Group, which lays out the basic requirements: Environmental Assessment, Civil Works (including drainage), cable and splice box procurement, Acceptance Testing, Project Management, etc) to install new cables (offering either 2x192 or 3x96 fibers), provides an example of a possible parallel geographic path (see below), and cost summary estimate.

Figure 7: Geographical locations of antenna pads and optical fiber paths

As a stand-alone project, the survey estimates a cost of approximately US$ 2.6M. However, should other construction take place, such as road upgrades and drainage improvements, or the installation of a secondary power line, significant cost savings could be realized from the potential synergies.

2.5 Charge 4 – Digitization Format

Charge description [AD2]:
The working group shall specify the number of basebands of data to be delivered to the correlator, and the number of bits in the transported data.

The, minimum, requirements requested under this charge are directly set by the recommendations made by the ALMA Frontend & Digitizer Specification Working Group in [RD2].

2.5.1 Number of basebands

From sections 6.3 “Instantaneous Bandwidth” and 7.1 “Digitizer Sampling Speed” in [RD2] it can be derived that the FE WG proposes one single, continuous baseband per sideband and polarization. This proposed FE / BE sub-system architecture directly dictates the baseband properties delivered via the DTS to the Correlator sub-system. In total 4 basebands, comprised of LSB and USB for 2, orthogonal, polarizations, will be made available at the input to the Correlator.

2.5.2 Number of bits

The FE WG in their report [RD2], section 7.2, advocate that the minimum number of effective bits of the digitizer (ENOB) shall be at least 5. This minimum ENOB value is based on a requirement for the digitizer efficiency, to be at least 99% for standard astronomical observations (excluding solar and calibration observations), for an input signal level dynamic range of 8.4 dB. This dynamic range should accommodate variations due to the sky brightness and amplitude ripple in the analogue signal chain preceding the digitizer.
Taking this minimum of 5 ENOB and assuming that a single baseband per polarization and sideband, as advocated in section 2.5.1, is transported by the DTS, the SCWG comes to a minimum

number of, physical, bits of 6 to be transported from the digitizer inside the BE sub-system to the input of the Correlator sub-system. The additional bit on top of the minimum ENOB should avoid any signal degradation due to uncertainties in the least significant bit (LSB), e.g. rounding errors, of the data to be transported.

In this context we must also emphasize that the use of ENOB to specify digitizer efficiency is an often overlooked but common source of confusion. ENOB is commonly used in, commercial, specifications of digitizers to quantify the noise contribution by the device. What should be realized is that this ENOB, as well as the alternative metric option quantization efficiency, is dependent on the, statistical, amplitude characteristics of the input signal. It is common practice, especially in commercial datasheets specifying a digitizer and sometimes without explicitly mentioning, that this input signal is a sinusoidal waveform. However, for radio astronomy applications like ALMA assuming a sinusoidal waveform is not a realistic assumption since the signal of interest has an, often Gaussian, amplitude distribution. Neglecting this issue can result in an erroneous noise contribution from the digitizer. A possibly more intuitive metric for specifying the digitizer, quantization, noise is its quantization efficiency as is advocated in [RD27]. Using this quantization efficiency, instead of ENOB, eases for example the system analysis as presented in section 2.7.3. But also for the quantization efficiency metric we must emphasize that it is dependent on the amplitude distribution of the input signal, as for ENOB, and this input signal condition should ideally be explicitly stated with both metrics. Also when verifying, e.g. through simulation or test, quantization efficiency and ENOB it shall be explicitly defined what the amplitude characteristics are of the input signal.

It is noted that the FE WG has, implicitly, assumed in their analysis of ENOB versus efficiency that the quantization levels are equidistant, as is traditionally the case in determining the optimal voltage levels for a given number of bits [RD43]. The use of non-equidistant quantization levels, optimized for the statistical properties of the input signal to be digitized, can result in a, slightly, lower ENOB for a given quantization efficiency. The use of non-equidistant quantization levels is common in e.g. digital voice communication but could in principle also be applied in an astronomical receiver system like ALMA. Details about this option are described in [RD4] Appendix B, section 5.

Strong justification for a stretch goal is not identified by either FE WG nor Correlator WG. On the basis of general system architecture considerations, the SCWG proposes to adopt 8 bits as the stretch goal for the number of bits to be transported from digitizer to Correlator sub-system. The number 8 is a power of 2 and 8 bits represents one single byte. Eight bits would accommodate a possible 8 bit digitizer generation providing some additional resilience to future sources of external RFI.

2.6 Charge 5 – Data Transport Format

Charge description [AD2]:
The working group, taking into account input from the FEWG and CorrWG and other sources, as needed, shall specify whether the data will be transported from the antennas to the correlator in its full time series, or after an initial Fourier Transform has been performed. The working group shall further specify the full list of information to be transmitted from the backends to the correlator, how the data will be packetized, the data transport protocol, the maximum

instantaneous data rate, and in the case that the correlator is located at the OSF, whether data can be transmitted to the OSF without any loss in integrity.

Based on the requirements for transmission data rate of 1.2 Tb/s per antenna and maturity of digital transmission technology, the working group and the CorrWG agreed to adopt optical Ethernet for the physical and data link layers. Ethernet type data protocols at 400 Gb/s are currently commercially available (400 GigE), and may then require fewer interfaces to other ALMA systems. It is widely adopted in industry, making development tools and resources readily available. At time of writing, GigE is also the proposed format for the ingest layer for the new Correlator proposal.

Moreover, the more traditional long haul data formats, such SONET and SDH are actually being phased out or discontinued in favour of the Ethernet protocol. A newer generation OTN (Optical Transport Network) protocol used in long haul communications was found to dissipate more power, due to the higher signal rate it requires, and Ethernet was again adopted as the format of choice. This serendipitously aligns with the recommendations of the previous sections.

As stated in 2.9.2, the current Timing Event (TE) signal can have jitter greater than the sampling period of 25 ps of 40 GSps. To keep synchronization between antennas in the correlator, digitized data must be transported after being time stamped. The time stamp should be initialized at the Clock Set Event (CSE) when a (sub-) array is created and keep synchronization with the sampling clock by referring 125-MHz reference. Synchronization between time stamps and the sampling clock must be maintained, free from TE jitters, while the (sub-) array is created. This manner of timing transport has been commonly established in VLBI via either recording or electronic.

VDIF (VLBI Data Interchange Format) is a standard format carrying time stamps and is used in the ALMA Phasing Project (APP). This format is technically mature with COTS formatters and compatible for APP2 and direct VLBI recording of a single antenna (without phasing). A VDIF data stream is capable to multiplex threads that correspond to digitizers for polarizations and sidebands. A VDIF packet for a single thread consists of a 32-byte data frame header and a data array up to 134 MBytes (65527 bytes for an UDP packet). Therefore, inserting VDIF header increases the traffic by 0.05%.

2.6.1 First F

As described in [RD1], at the ALMA 2030 Correlator Workshop there was near consensus that an initial coarse channelization will be necessary, implying an FFX architecture. This channelization was referred to as the "first F". However, the term "first F" can carry different connotations for different readers. In a strict sense, it implies the use of a Fourier transform to convert the raw data from a timeseries to a frequency spectrum. A broader definition includes the concept of a "digital down conversion" in which different pieces of the broadband signal are extracted and resampled to a lower rate but remain as timeseries data fundamentally[2]. Appendix A.2 of [RD1] describes the significant difficulties caused by performing a true Fourier transform upstream of the correlator and indicate a strong preference against it, regardless of its location (i.e., in the antenna or not). However, a digital down conversion does not incur the many disadvantages of a Fourier transform, such as the delay correction needing to be applied prior to that step. Hence, it remains an open question as to whether the ALMA 2030 system shall perform a coarse channelization via digital

---

[2] In a sense, the current ALMA architecture can be considered as effectively a "first F" in that the wideband receiver IF output is sampled and transmitted as four discrete basebands.

down conversion at the antenna, or further downstream. If a single high-speed digitizer proves infeasible, then performing the channelization in the antenna would be an advantage. In that case, two digitizers would be needed to cover the 2-20 GHz IF range, operating in the first and second Nyquist range, respectively, and would represent the initial channelization. In any case, if a coarse channelization is to be performed in the antenna, then using a fixed-tuned channelization (such as a regular grid of 8 x 2 GHz subbands or 80 x 200 MHz subbands) might be preferable over a tuneable channelization as it would avoid the need for the control software to command the hardware in each antenna specifically for each observation. In any case, as noted in [RD1] and [RD2], the requirements of the data transport system, costs, and any practical limitations of technology should drive the choice of architecture.

2.7 Charge 6 – System

Charge description [AD2]:
The working group shall consider all derived specifications by the FEWG, the CorrWG, including the potential Correlator locations, and this WG and assess if additional System Requirements applicable to the part of the system between FE and Correlator are necessary towards the ALMA 2030 objectives. If this is the case, the working group shall specify the necessary additional requirements.

2.7.1 Electrical Power

Table 1 is an updated version of Table 6 of [RD11] by adding monthly energy generation in 2019 [RD12]. The total average power demand of the ALMA determined in [RD11], 2,536 kW, is still useful to consider the power demand of the ALMA towards ALMA 2030.

Table 1 : Monthly energy generation in 2016, 2017, 2018, and 2019. All monthly datasets have been referred from [RD12]

	Energy 2016 [kWh	**Energy 2017[kWh]**	**Energy 2018 [kWh**	**Energy 2019 [kWh]**
January	1,730,689	1,787,950	1,830,918	1,753,124
February	1,117,608	1,140,146	624,980	753,740
March	1,720,515	1,767,738	1,766,404	1,719,887
April	1,650,353	1,759,784	1,819,660	1,756,649
May	1,720,044	1,904,434	1,920,344	1,805,571
June	1,773,323	1,851,628	1,930,412	1,947,996
July	1,914,698	1,917,854	1,912,673	1,943,450
August	1,908,514	1,978,351	1,947,687	1,829,116
September	1,821,060	1,873,166	1,896,846	1,787,908
October	1,754,352	1,927,698	1,866,832	1,793,700
November	1,685,162	1,819,110	1,803,836	1,732,168
December	1,776,234	1,863,998	1,813,072	1,853,608
Total [MWh/year]	20,572.55	21,591.86	21,133.66	20,676.92
Power Average [kW] with February	2,342	2,465	2,413	2,360
Power Average [kW] without February	**2,413**	**2,529**	**2,536**	**2,463**

Table 2 shows power demands of the existing correlators (BLC, ACAC) and the projects which will be deployed in ALMA before ALMA 2030. The power demands of the BLC, the ACAC, and the ACAS don't include power consumption of their HVAC systems of the AOS-TB (AHU-1, AHU-2, AHU-6, etc).

*Table 2 Power demands of the existing correlators and development projects planned before ALMA 2030. *1: subtracting the safety margin (4.7 kW) from the total power demand (20.4 kW)*

Correlator/Project	**Location**	**Power Consumption [kW]**	**Reference**
Baseline Correlator (BLC)	AOS	180	[RD13], [RD14] Hardware: 160 kW, Computing: 20 kW
ACA Correlator (ACAC)	AOS	77	[RD15], [RD16], NCR-44 Hardware: 65 kW, Computing: 12 kW
ACA Spectrometer (ACAS)	AOS	7.7	[RD15], [RD16], [RD17], [RD18]
OSF indoor sports facility	OSF	44.7	Maximum demand [RD19]
HiL simulation environment	OSF	15.7 (*1)	[RD20] 2-ant correlator: 5.4 kW [RD21]

We assume that changes of power demands in each sub-system except for the correlator sub-systems and their HVAC systems are almost zero (or less) in ALMA 2030 to keep the specifications of the HVAC system in the antennas as described below.

FrontEnd

- No change of the power demands in CCAs, WCAs, cryogenic sub-system, and other FE instruments that are mounted on an antenna.

BackEnd

- No change in the BE-LPRA located in an antenna and the BE-CLOA located in the AOS-TB.
- No change of the power demand in the BE-AA mounted in the BE analog and digital racks. The power demand of the BE-AA shall not exceed 2 kW in total [RD22].
- No change of the power demand in the BE-FOMA in total. However, since the EDFA modules of the FOAD racks are not mounted now, an actual power demand of the BE-FOMA will increase in ALMA 2030 slightly.
- The BE-DRXA should be considered as a part of the 2nd generation correlators.

Others

- The computing systems located in the AOS-TB and the OSF will be upgraded in ALMA 2030 but no increase of the power demand is assumed in this section because microprocessor power consumption for typical CPUs and GPUs has remained relatively constant in the past 15 years.

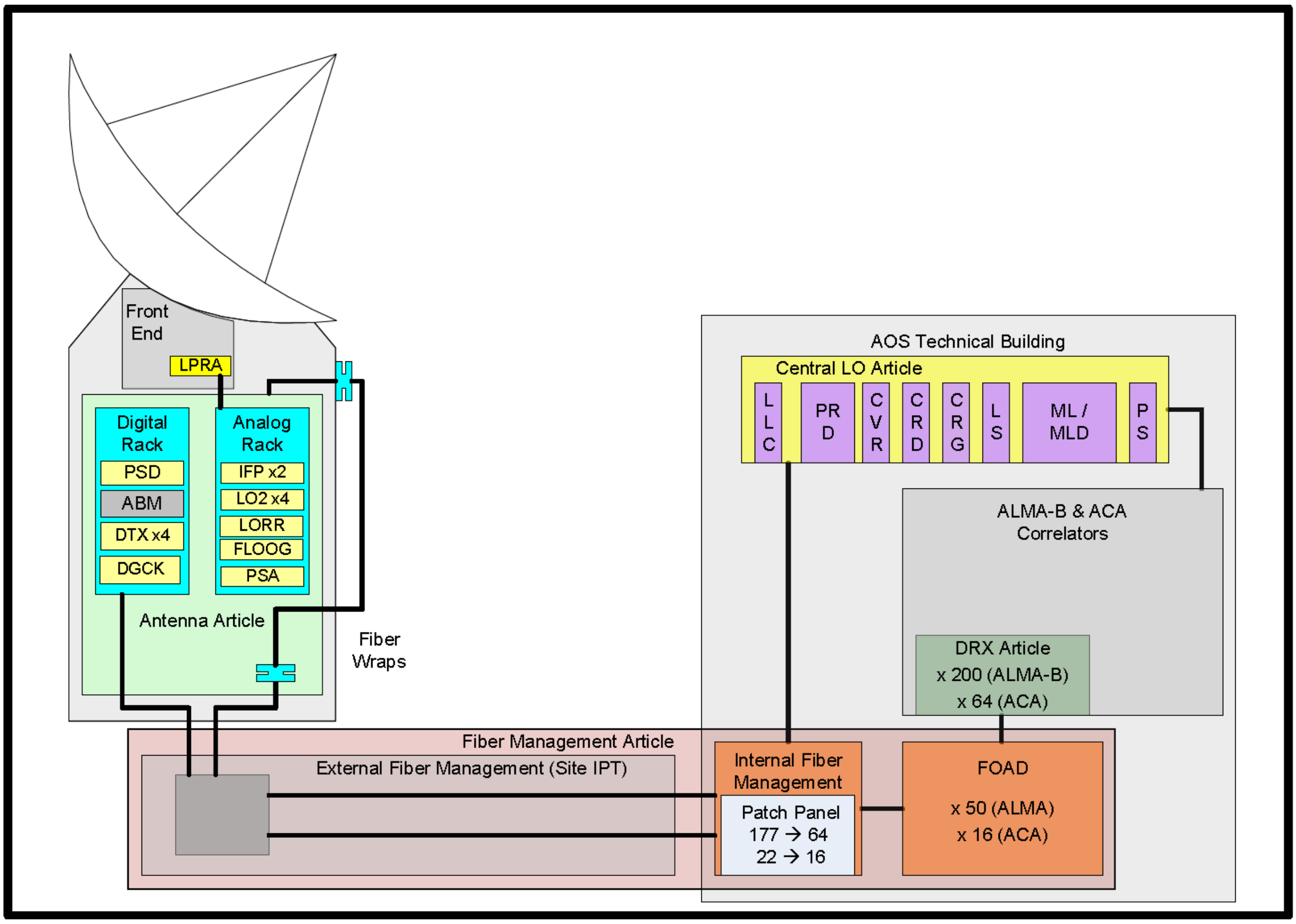


Figure 8: Existing BE Sub-system Top Level Diagram [RD23].

To estimate the available power capacity remaining in a single GT for the 2nd Generation correlator and its HVAC system, the following notional phases are assumed (where it is further assumed that the correlator will be delivered in four quadrants). These estimates are not intended to represent any specific correlator proposal.

- Phase 0: Science observations using the BLC and ACAC (as of 2021)
- Phase 1: Deployment of the ACA Spectrometer, the HiL simulation environment, and the OSF indoor sports facility in 2022 or 2023
- Phase 2: Launch of the 1st quadrant of the 2nd generation correlator
- Phase 3: Launch of the 2nd quadrant of the 2nd generation correlator
- Phase 4: Deployment of all four quadrants of the 2nd generation correlator with operating the BLC, the ACAC, and the ACAS.
- Phase 5: Decommissioning of the BLC, the ACAC, and the ACAS, assuming the DRXP modules of the ACAS will not be upgraded for the new DTS.

Table 3 shows estimations of available power capacity for the 2nd generation correlators and its HVAC system in each notional phase, assuming a power demand of the 2nd generation correlator will not exceed the total power demand of the BLC, the ACAC, and the ACAS, 265 kW.

Table 3 Estimation of the observatory power demands in ALMA 2030

	Phase					
	0	1	2	3	4	5
Power capacity of one GT [kW]	2,823	2,823	2,823	2,823	2,823	2,823
Power demand excluding BLC & ACAC [kW]	2,279	2,279	2,279	2,279	2,279	2,279
BLC [kW]	180	180	180	180	180	
ACAC [kW]	77	77	77	77	77	
ACAS [kW]		7.7	7.7	7.7	7.7	
HiL simulation environment [kW]		15.7	15.7	15.7	15.7	15.7
OSF indoor sports facitliy [kW]		44.7	44.7	44.7	44.7	44.7
Power demand excluding the 2nd gen corr [kW]	2,536	2,604	2,604	2,604	2,604	2,339
Power demand of the 2nd gen correlator [kW]			66	133	265	265
Estimated power demand [kW]	2,536	2,604	2,670	2,737	2,869	2,604
Remaining power capacity [kW]	287	219	153	86	-46	219
Average power usage [%]	90%	92%	95%	97%	102%	92%

In this estimation, the power demands of the existing HVAC systems in the AOS-TB and a new room of the 2nd generation correlator are not estimated explicitly. Looking at the past correlator room HVAC study [RD24], a power demand of an HVAC system located in the OSF was 137.2 kW in air conditioning mode, assuming 200 kW thermal load a the OSF. If we simply scale up the value using 265 kW thermal load of the 2nd generation correlator, a power demand of an HVAC system for a new correlator room located in the OSF will be about 180 kW. It can be concluded that one GT will be able to supply the required electrical power after decommissioning the BLC, the ACAC, and the ACAS (phase 5), given the lower monthly power demand in summer and a decrease of the power demand by stopping the HVAC systems for the correlators in the AOS-TB. Meanwhile, two GTs' operation will be required between phase 3 and phase 4.

2.7.2 Correlator location

We agree with the CorrWG that the OSF location will be optimal to deploy the 2nd generation correlator, considering several aspects pointed out by them [RD1]. The following spaces will be required to deploy the 2nd generation correlator, BE subsystems (including upgraded FOAD racks and reference and timing signal distributors), and a new HVAC system in the OSF.

- New Correlator Room: 110 m^2 or more
- New BackEnd Room: TBD m^2
- FOAD racks (Qty 5 or more, 0.6 m^2 per rack), reference and timing signal distributors, other BE auxiliaries
- HVAC system: TBD m^2

Initially, the OSF antenna assembly complex where the 2-antenna correlator has been operated was considered to be a candidate place to deploy the 2nd generation correlator and BE subsystems (Figure 9, Figure 10, Figure 11), allowing for future expansion or upgrade of the 2nd generation correlator and related BE subsystems. More recently, a portion of the current Control Room has emerged as a favourable option with more area (Figure 12). Regardless of the location, the existing HVAC systems of the OSF technical facility are not capable to cool the expected thermal load of the 2nd generation correlator (265 kW) [RD34]. A new HVAC system will need to be installed such as the HVAC system for the HiL simulation environment [RD20], and air cleanliness of the new rooms will comply with requirements from the 2nd generation correlator, the FOAD racks, and BE auxiliaries. As mentioned in section 2.7.1, our remaining concern is how much a new HVAC system for the 2nd Generation Correlator will consume electrical power. A detailed design of a new HVAC system for the 2nd generation correlator should be established by HVAC specialists as well as the past correlator room HVAC study [RD24].

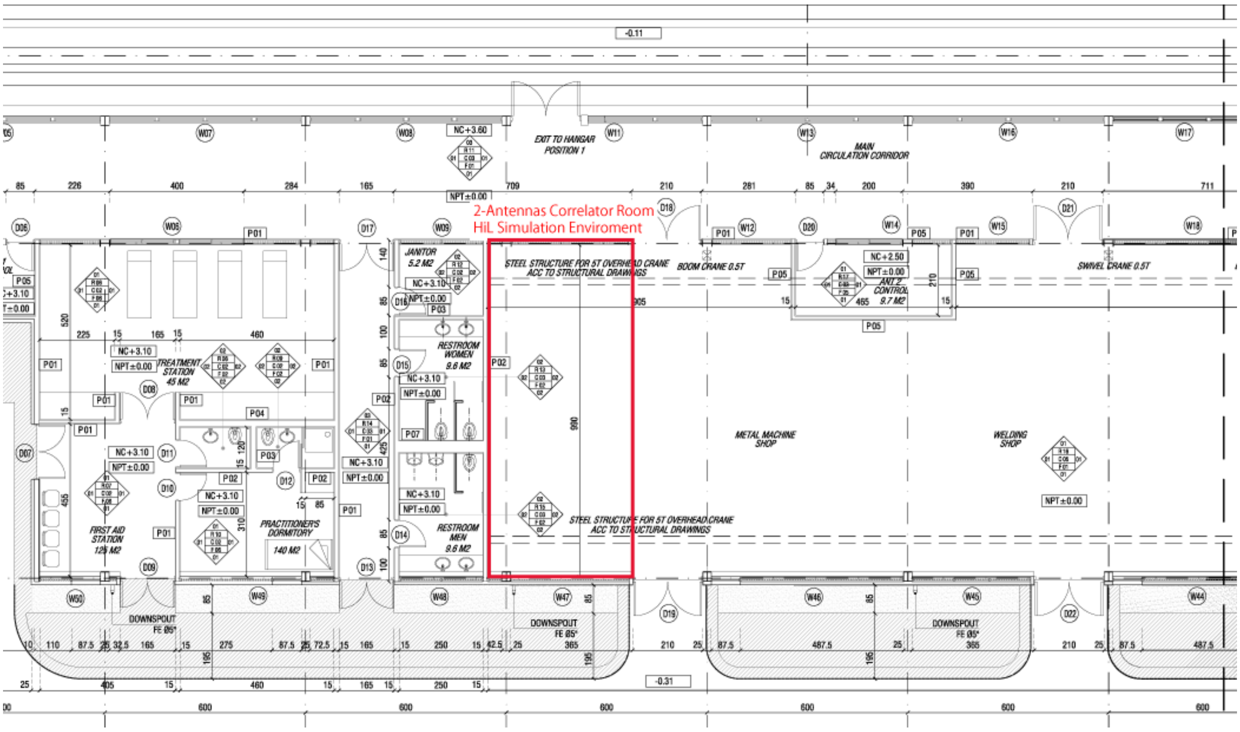


Figure 9: 2-antennas Correlator Room (HiL Simulation Environment) in the Antenna Assembly Complex (Hanger) marked as a red box (SITE-20.08.08.03-007-0-DWG)

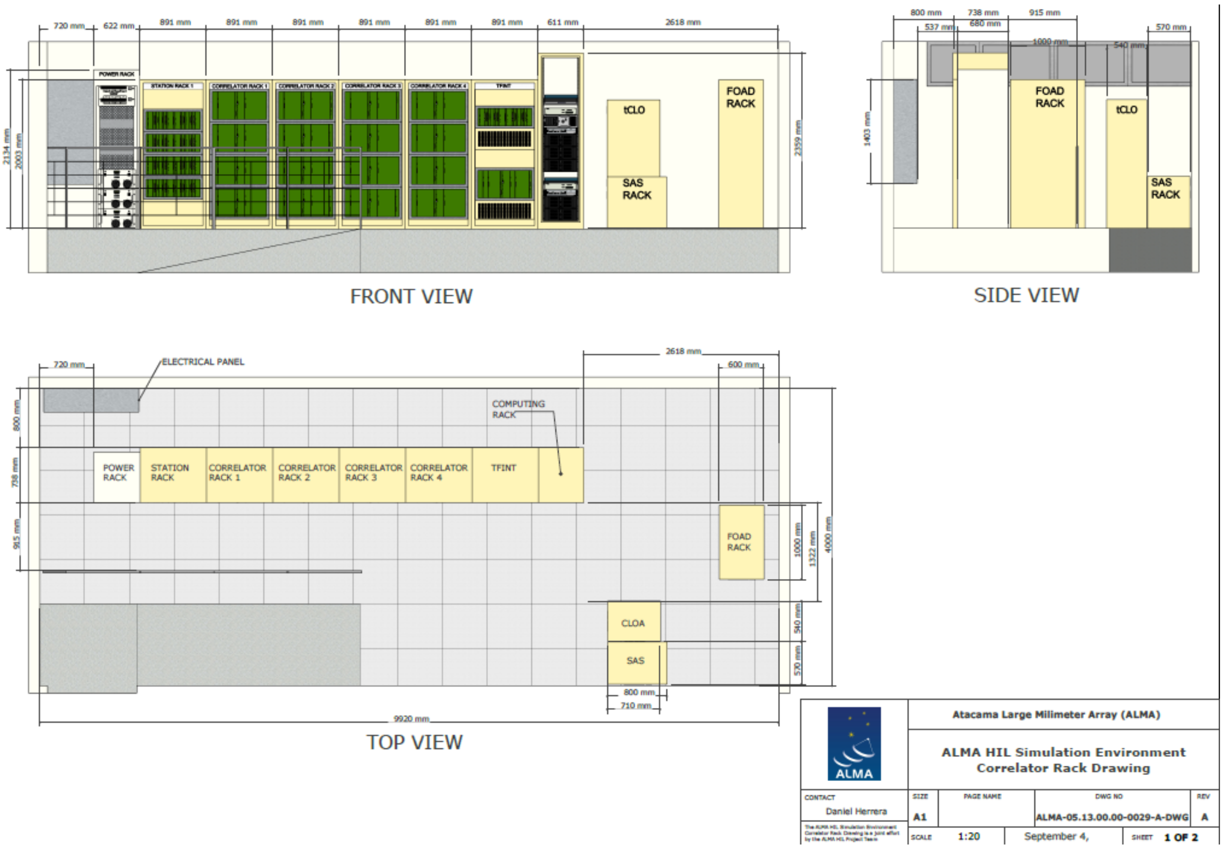


Figure 10: Floor Plan of the HiL Simulation Environment in the 2-antennas Correlator Room [RD20]

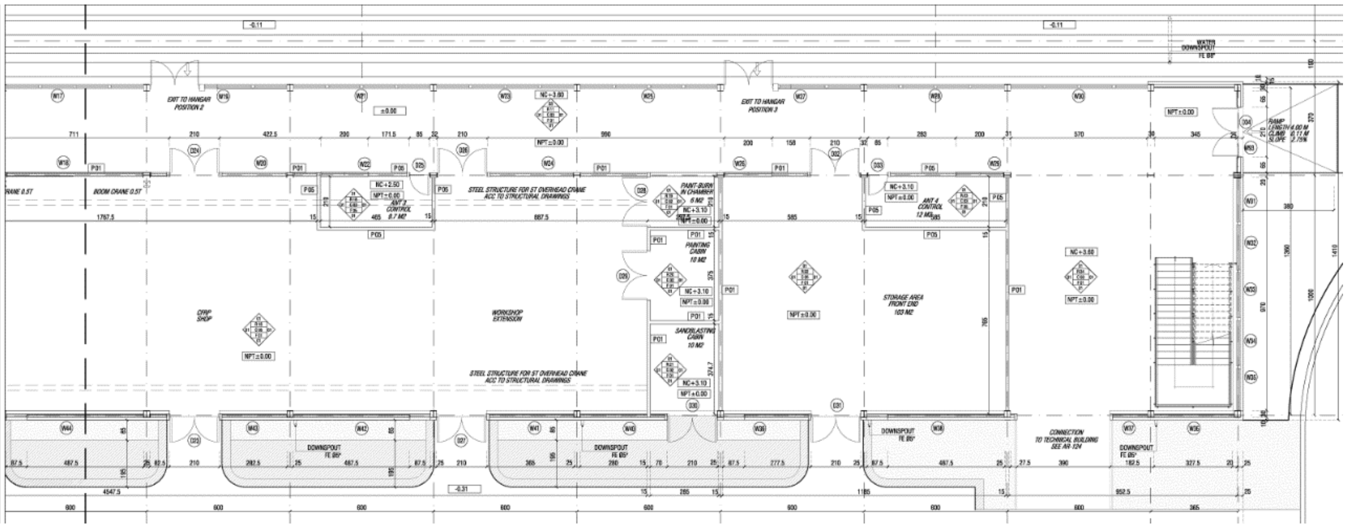


Figure 11: South side of the Antenna Assembly Complex (Hanger) (SITE-20.08.08.03-008-0-DWG)

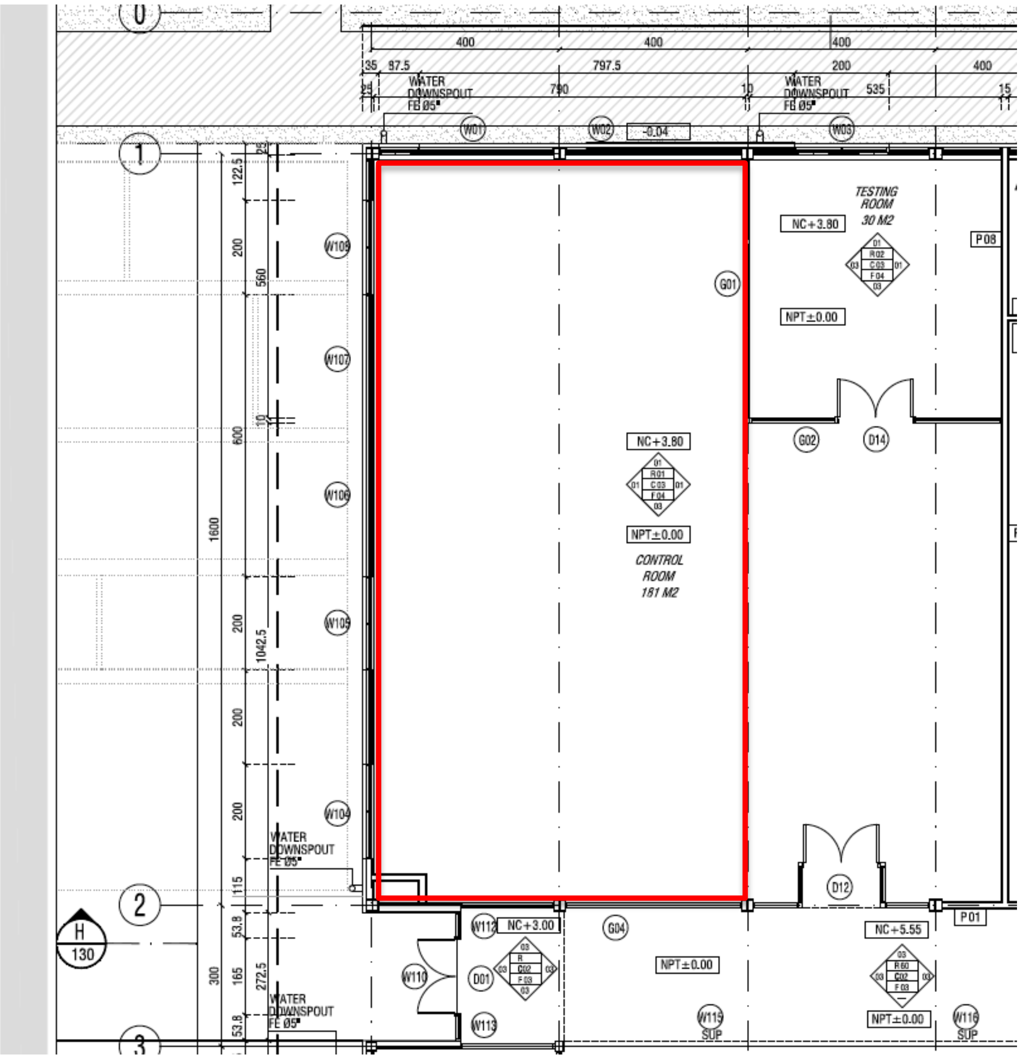
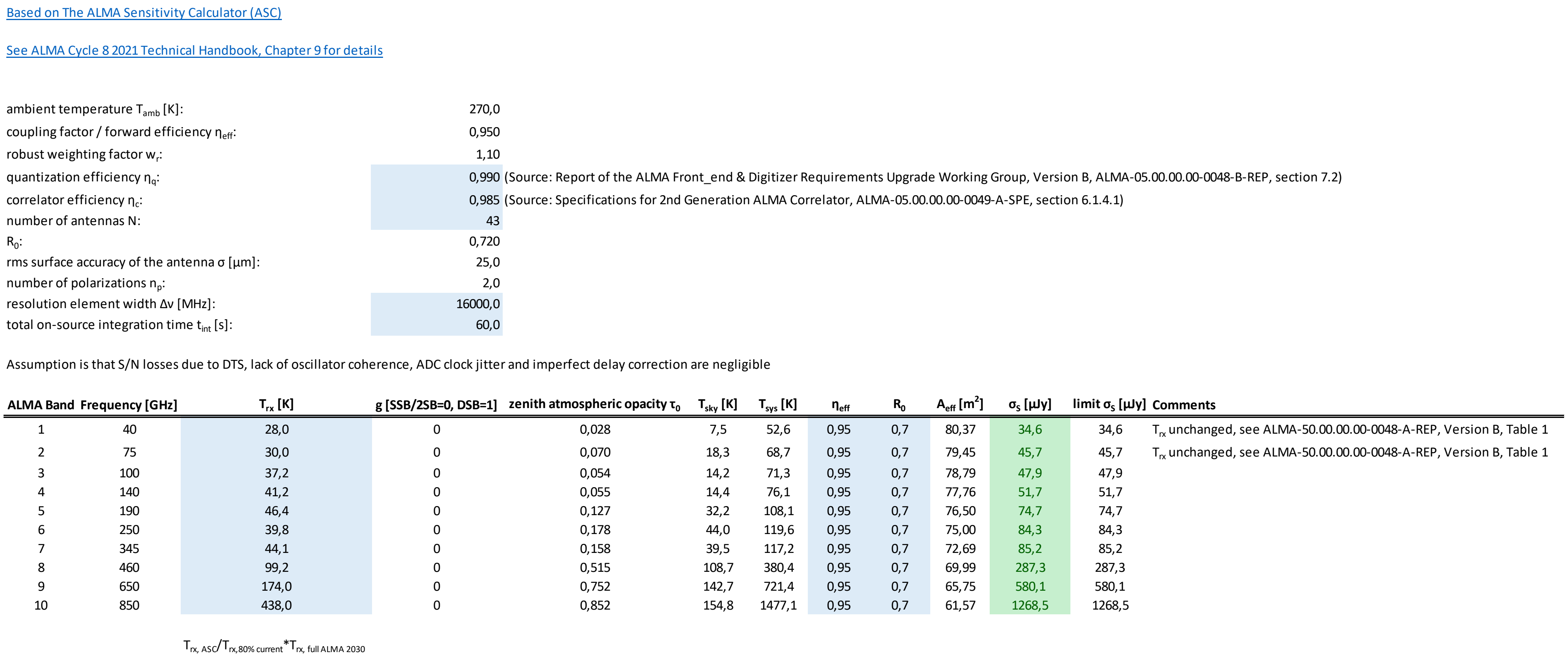


Figure 12: Current control room and Testing room (SITE-20.08.10.03-004-0-DWG)

2.7.3 System sensitivity/performance allocation

To support the final design of the ALMA 2030 system architecture a simple Excel spreadsheet, see snapshot in Figure 13, has been developed to assess contributions from the sub-systems in the end-to-end, including both analogue as well as digital components, signal chain. The spreadsheet calculates continuum sensitivity for all 10 ALMA Bands following the procedure used in the ALMA Sensitivity Calculator as described in Chapter 9 of [RD39]. The various parameters used in the calculation have been obtained from [RD1], for the 2nd Gen Correlator, [RD2] for the new FE and digitizer products, and [RD39]. The receiver noise temperatures T_{rx} adopted in the spreadsheet are based on the values recommended in [RD2]. Since these values are upper, worst case, limits and actual performance is expected to be better, the T_{rx} values have been adjusted by a correction factor. This correction factor is based on the ratio of the actual receiver noise temperature and its specification, iow. upper limit, of the current ALMA receivers.

It is emphasized that the purpose of this tool is not to accurately predict continuum sensitivity but primarily a tool that allows an analysis of performance trade-offs between sub-systems.



Based on The ALMA Sensitivity Calculator (ASC)

See ALMA Cycle 8 2021 Technical Handbook, Chapter 9 for details

ambient temperature T_{amb} [K]:	270,0	
coupling factor / forward efficiency η_{eff}:	0,950	
robust weighting factor w_r:	1,10	
quantization efficiency η_q:	0,990	(Source: Report of the ALMA Front_end & Digitizer Requirements Upgrade Working Group, Version B, ALMA-05.00.00.00-0048-B-REP, section 7.2)
correlator efficiency η_c:	0,985	(Source: Specifications for 2nd Generation ALMA Correlator, ALMA-05.00.00.00-0049-A-SPE, section 6.1.4.1)
number of antennas N:	43	
R_0:	0,720	
rms surface accuracy of the antenna σ [μm]:	25,0	
number of polarizations n_p:	2,0	
resolution element width Δν [MHz]:	16000,0	
total on-source integration time t_{int} [s]:	60,0	

Assumption is that S/N losses due to DTS, lack of oscillator coherence, ADC clock jitter and imperfect delay correction are negligible

ALMA Band	Frequency [GHz]	T_{rx} [K]	g [SSB/2SB=0, DSB=1]	zenith atmospheric opacity τ_0	T_{sky} [K]	T_{sys} [K]	η_{eff}	R_0	A_{eff} [m^2]	σ_S [μJy]	limit σ_S [μJy]	Comments
1	40	28,0	0	0,028	7,5	52,6	0,95	0,7	80,37	34,6	34,6	T_{rx} unchanged, see ALMA-50.00.00.00-0048-A-REP, Version B, Table 1
2	75	30,0	0	0,070	18,3	68,7	0,95	0,7	79,45	45,7	45,7	T_{rx} unchanged, see ALMA-50.00.00.00-0048-A-REP, Version B, Table 1
3	100	37,2	0	0,054	14,2	71,3	0,95	0,7	78,79	47,9	47,9	
4	140	41,2	0	0,055	14,4	76,1	0,95	0,7	77,76	51,7	51,7	
5	190	46,4	0	0,127	32,2	108,1	0,95	0,7	76,50	74,7	74,7	
6	250	39,8	0	0,178	44,0	119,6	0,95	0,7	75,00	84,3	84,3	
7	345	44,1	0	0,158	39,5	117,2	0,95	0,7	72,69	85,2	85,2	
8	460	99,2	0	0,515	108,7	380,4	0,95	0,7	69,99	287,3	287,3	
9	650	174,0	0	0,752	142,7	721,4	0,95	0,7	65,75	580,1	580,1	
10	850	438,0	0	0,852	154,8	1477,1	0,95	0,7	61,57	1268,5	1268,5	

$T_{rx,\,ASC}/T_{rx,80\%\,current}*T_{rx,\,full\,ALMA\,2030}$

Figure 13 ALMA continuum sensitivity / performance allocation spreadsheet

2.7.4 Delay tracking, fringe stopping, Walsh phase switching and LO offsetting

The current ALMA delay tracking system is summarised in Appendix B of [RD4]. Delay tracking in ALMA 2030 has been discussed within the Correlator requirements WG, and relevant sections of the current draft of their report [RD1] are:

- 6.1.4.2 Sensitivity loss due to imperfect delay correction
    - It is noted that the formula provided in this section is for the maximum instantaneous coherence loss, and the time-averaged coherence loss is considerably lower (e.g., by a factor of 8 for the current system)
- 6.1.5 Maximum Delay compensation distance, buffer time range, and buffer capacity
- 6.3.4 Maximum delay rate
- A.3 Considerations related to Delay Correction
    - A.3.1 Comparison of FFT segment time as a function of assumed sample rate and finest spectral resolution
    - A.3.2 Delay correction strategies

Some notable points:

1. The new correlator is assumed to be of (F)FX design, which means a fine (sub-sample) delay correction could be applied within the correlator per FFT segment, by adjusting the phase vs. frequency (for example as implemented in the MeerKAT radio telescope [RD10]); the update rate will be limited by the FFT segment length, which is driven by the maximum required number of channels
2. Fine (sub-sample) delay correction can also be achieved in digital signal processing with a fractional delay filter, which although having poor response near the Nyquist frequency, if performed on oversampled sub-bands produced by a “first-F” the performance can be acceptable, and this approach avoids dependence on the FFT segment length of the final ‘F’ of the correlator
3. The maximum delay rate requirements are 8.5ns/s minimum and 34ns/s as stretch goal, which are about 2—8 times what ALMA currently supports
4. It is assumed that the receiver IF will be sampled by a 40Gs/s ADC operating in the first Nyquist zone with maximum sampled frequency of 20GHz; this implies a pre-correlation delay step size should be at least 5 times finer than currently (based on 4GHz max. sampled frequency in the 2nd Nyquist zone)
5. Depending on overall system sensitivity/efficiency requirements, it may be necessary to decrease the delay step size further than simply extrapolating the current ALMA fine step size to the higher sampled frequency
6. For 1% max. sensitivity loss with the longest anticipated baselines and sidereal tracking, [RD4] section 6.1.4.2 shows that the required delay update periods are down to about 0.230ms for the minimum goal E-W baseline length or 0.134ms for the stretch goal; thus we should be thinking around 0.1ms for low sensitivity loss. However, these numbers are pessimistic as they take an instantaneous worst-case coherence loss rather than an average over time (the same calculation for the current system yields 2.5% maximum loss, but the average on a baseline is only about 0.3%)
7. It is desirable to implement the fine delay tracking independently per signal path, i.e., per IF and per polarisation, in order to simplify phased array operation (which cannot have post-correlation residual delays applied to the phased-sum data).

A major remaining question is whether there is a need for fine delay correction upstream of the correlator, e.g., in the DGCK as we currently do. This decision depends on:

1. The FFT segment lengths supported by the correlator, or
2. Feasibility of using fractional delay filters and their performance,
3. The maximum allowed sensitivity (coherence) loss at a maximum delay rate
4. The technical feasibility of performing DGCK phase steps of 1/16 of a cycle on timing boundaries of 0.1ms that are synchronised either with the correlator or with the data timestamping by the digitiser/DTS in the case of an asynchronous DTS.

2.7.4.1 Feasibility of DGCK phase control per signal path

Although the digitisers are assumed to sample at >=40GS/s, due to requiring interleaved cores to achieve this high rate the digitiser clock will be at a sub-multiple of the sample rate, quite likely at 20 GHz. At this frequency there are relatively inexpensive (<US$ 100) off-the-shelf PLL RF generator and VCO ICs available with suitably low phase noise. These would phase-lock the digitiser clock produced by a VCO to the 125MHz ALMA timing reference signal via a programmable frequency divider. Additionally, some such ICs implement a programmable phase offset that could be used to implement fine delay tracking (an example device the WG looked at is the TI LMX2820[1]). Although enabling the phase offsetting feature in an otherwise integer-N configuration may add some complications by way of spurious signals to ensure filtering of, such an implementation for the DGCK seems feasible. The relatively low costs, component counts and power consumption mean that implementing a separate clock per digitiser (signal path) is also feasible.

Fine delay steps implemented by the DGCKs must be synchronised with the rest of the delay tracking that is performed by the correlator. In the present system it is not uncommon for this synchronisation to break down for various reasons. As described in section 3.2, we anticipate that the DTS will operate asynchronously, and therefore all timing will now be determined at the antenna. Maintaining synchronicity between DGCKs and the data timestamping imparted by the digitisers/DTS should be relatively straightforward, as these devices will likely be closely co-located, and directly interfaced to each other.

Communication of the sequence of commanded delays to the antennas in addition to the correlator remains an additional complexity in this scheme. The addition of multiple DGCKs only adds a small extra complexity to this as there need be only a single commanded delay stream plus a set of signal path offsets that would be updated infrequently. We do anyway need to provide some minimal delay tracking information to the antennas for phase tracking of the LO1.

Thus DGCK-based fine delay correction, including with a correction per signal path, does appear feasible for ALMA 2030. We note however that lab demonstration of this in the near future is desirable, to ascertain the performance really offered by commercial PLL/VCO ICs with suitable programmable phase control.

2.7.4.2 Preliminary recommendation on delay tracking in ALMA 2030

Coarse delay correction will be performed at the correlator input, potentially combined with a DTS buffer to allow for the asynchronous communication. Residual post-correlation delay correction by the correlator subsystem (either in hardware or software) will remain needed.

For the fine delay tracking, at present it appears that both correlator-based correction (either phase slope per FFT segment, or fractional delay filter following an oversampling "first-F"), and DGCK phase based schemes are feasible and well suited. The DGCK based scheme has the advantage of decoupling the delay tracking scheme from the DSP/correlator architecture (FFT segment length and/or first-F design), however, it pushes more of the delay tracking to the antennas and adds some small extra hardware complexity. Unlike in the present system, synchronisation of delay updates by antenna and correlator should be less of a concern due to the asynchronous DTS which implies all synchronisation is determined at the antenna only. However, as the concern of sensitivity loss due to post-FFT fine delay correction raised in the correlator working group report seems pessimistic (being an instantaneous worst-case rather than a time average), and as the justification for the use of the stretch goal spectral resolution is not very strong, especially for use with the longest baselines, a correlator-based post-FFT fine delay correction also appears well suited to ALMA 2030. As a first-F may be necessary to break the full digitised bandwidth into chunks that can be processed by the FFT stage in the correlator, fractional delay filters may also be a suitable choice for ALMA 2030.

Summary: three options remain viable (hardware DGCK clock modulation, post-FFT phase slope correction, and fractional delay filters after an oversampling filter bank) and should be assessed on the merits of each design proposal in terms of performance, complexity, and cost.

2.7.4.3 Walsh sequence phase switching

The proposed signal chain upgrade for ALMA 2030 does not necessarily bring any changes to the Walsh switching implementation. The first switching (modulation) stage for both 90- and 180-degree Walsh modes will remain on LO1 via the FLOOG. For 90 degree Walsh the demodulation will still be done by the correlator post-correlation.

For the 180 degree Walsh demodulation, it is necessary to decide where to implement this. At present it is done in the DTXs by flipping the sign bit of the digitised data. Depending on the coding scheme for the new digitiser modules, this may again be the optimum implementation. It could however be carried out at any point between the digitisers (or their clock) and the correlator antenna-based processing (given that the data at the correlator will have been timestamped at the antenna, synchronisation should not be an issue). Nominally it is suggested to apply the 180 degree Walsh demodulation within the new digitiser/DTS module on the digital data, as done at present. However, other options could be considered if this proves challenging. Keeping the demodulation within the antenna electronics retains the simplicity that the correlator does not need to know anything about 180 deg Walsh.

Potential improvements to 90 deg Walsh sideband separation

An issue with the current Walsh switching implementation is the long (2.048 second) duration 90 degree switching cycle. The functioning of this method of sideband separation neglects the fact that the atmosphere above each antenna is also modulating the phases, and over 2 seconds this can be enough to reduce the sideband rejection within individual integrations to be as low as about -10dB on some baselines (over time it averages down to much better values as the phase of the sideband leakage is random, but it leaves an incoherent noise contribution and possible systematic errors in the *uv* domain).

Ideally, we would either reduce the cycle duration, and/or increase the number of available sequences beyond 128 (but retaining the same sequence duration) so that antennas can be allocated sequence numbers with greater separations that then result in less time in the same baseline phase switch state. Both of these options mean reducing the switching period from the current 16ms. Given FFT segment lengths of order 0.1 to 1ms, reducing the switching period is likely to have an adverse effect unless it is possible to exactly choose the FFT segment length to be a sub-multiple of the Walsh switching period. This, however, seems an un-warranted constraint on the correlator by a mode that is intended to be phased-out in favour of 2SB Band 9 and 10 receivers. **Thus, it is not recommended to modify the 90 degree Walsh sequence implementation.**

It is noted that if the correlator can correlate the full IF bandwidth in both sidebands, then sideband separation can better be achieved by LO frequency offsetting and correlating the two sidebands independently, as the free correlated bandwidth doubling resulting from the post-correlation 90 degree Walsh demodulation is not needed to correlate the full bandwidth in both sidebands.

2.7.4.4 LO offsetting

LO frequency offsetting is used for sideband suppression and as a suppression of correlated IF spurii. At present this is implemented in three stages: LO1 (FLOOG), LO2, and the correlator TFBs. As the ALMA 2030 design will lack an LO2 conversion, the LO offsetting demodulation will always need to be done by the correlator/DSP. This could, for example, be implemented in a “First F” down-conversion as in the current TFBs, Otherwise, there should be no significant difference to this feature.

Summary: must be implemented in correlator/DSP; otherwise no significant changes

2.7.4.5 Fringe tracking/stopping

It is expected that fringe stopping in ALMA2030 will be carried out using small frequency offsets in the FLOOG, as is done now. There is no loss in the removal of the second LO conversion; in fact, this is a simplification. Fringe stopping could potentially also be implemented in DSP, however, after the first LO conversion (without the fringe tracking applied there) it should be noted that different corrections are required for each sideband, causing a problem for post-correlation sideband separation by 90 degree Walsh switching.

2.8 Charge 7 – Interfaces

Charge description [AD2]:

The working group shall assess the existing interfaces between FE, Digitizers, BE, DTS and Correlator and shall identify the interfaces and related ICDs to be updated in relation to the update of the Technical System Requirement towards the ALMA 2030 objectives. They shall assess the impact of the updated requirements on the interfaces between the part of the System between FE and Correlator and the rest of the ALMA system, which shall be assessed further by a System Requirements Working Group (to be established) and the IET, ICT and ISOpT, as relevant.

The analysis of interfaces is organized following the ALMA Product Tree [RD25] and limited to those products at Level 0 or Level 1 [RD35].

2.8.1 Interface requirements between FE and BE

In the current ALMA system architecture the interface between Frontend and Backend is split and described in two ICDs [RD31] and [RD32].

2.8.1.1 Interface between Front End / IF and Back End / IF Downconverter

With the obsolescence of the IF Processor Sub-subsystem (IFPS) in the ALMA 2030 system architecture, see section 2.3.1, also the Interface between Front End / IF and Back End / IF Downconverter [RD31] becomes obsolete.

This ICD shall be replaced by one which takes into account the new system architecture which might be based on a dedicated, optical, link, e.g. using Samtec FireFly technology (https://www.samtec.com/optics/optical-cable/mid-board/firefly) [RD27], from the FE-Assembly to the Digital Backend Rack. A new ICD shall be developed as part of the preliminary design phase of the relevant products. The ICD shall define:

- Mechanical interface requirements, including connector standards;
- Opto-electrical interface requirements.

In order to accommodate the wider IF range of the upgraded receivers, the current 2-4 GHz anti-aliasing filter (with digitizers operating in the 2nd Nyquist zone) shall be replaced with a wider filter commensurate with the proposed sampling of the 1st Nyquist zone, 0 - 20 GHz, having a few hundred MHz roll-off on each side [RD27].

This means that a large portion of out-of-band signal from the legacy receivers (e.g., 2 - 4 and 8 - 20 GHz for Bands 3, 4, 5, 7, 8) will reach the new digitizers. The original Front End specifications did limit the out-of-band power from 30MHz - 18GHz to be within 3 dB of the in-band power. So this wide-band signal should not cause a problem under the assumption that the power spectral density (ripple) out-of-band is below the nominal in-band power spectral density. To avoid desensitization of the new digitizers, in other words a loss of quantization efficiency due to increased ripple of the to be digitized input signal, an additional requirement on out-of-band spectral power density shall be introduced.

However, tones from the YIG oscillators in various local oscillators will be in the wider IF range. The impact of these CW tones on the digitizer quantization efficiency should be negligible as long as their power is substantially less compared to the nominal in-band power. Proper design and manufacturing techniques providing sufficient shielding between oscillator signals and digitizer inputs should avoid this problem.

Still these oscillator signals, as well as their mixing products due to non-linearities in the signal chain, can coincide with the IF range and be detected as spurious. Unfortunately, this phenomenon is unavoidable in wide-band receivers like the ALMA system. Good engineering practices, shielding, and additional mitigation techniques, 180° phase switching and LO-offsetting, should minimize these spurious products as much as possible.

2.8.1.2 Interface between Front End First Local Oscillator and Back End LO References

Regarding LO1, the upgraded receiver bands may employ higher frequency YIG oscillators in the WCAs so that the fundamental frequency lies above the expanded IF range, as is planned for Band 6 upgrade (see section 3.1.3). In this case, a change in the multiplier harmonic value will need to be stored in the TMCDB, and on a per-antenna basis as it will likely require several months to completely replace a receiver band on all antennas.

Regarding LO2, it will become obsolete in the ALMA 2030 System Architecture if the second analogue down-conversion step is eliminated, as is expected. Therefore, some of the LO Offsetting and Fringe tracking/rotation functions might have to be implemented in the FLOOG, as proposed in sections 3.7 and 3.8 of [RD4].
The exact minimum requirements for phase resolution and frequency resolution / offset range applicable to the FLOOG shall be determined by the, to be established, System Requirements Working Group. These requirements shall be included in an update of the ICD [RD32].

2.8.2 Interface requirements between BE and Correlator

See Section 2.9 below

2.8.3 Interface requirements between BE and Software

This is largely covered currently in Charge 1 – Software Operating Environment, section 2.1, although not at the detailed level, e.g. monitor and control items, as required for an Interface Control Document. This is a topic that needs further iteration between the responsible stakeholders involved (ICT, instrument development teams, system engineers etc.) is part of the design phases.

We expect the current BE-SW ICDs summarized below will be affected by the ALMA 2030 upgrade.

BE Device	ICD	ALMA 2030
IFProc	ALMA-52.00.00.00-70.35.30.00-C-ICD	REMOVED
LO2	ALMA-55.05.00.00-70.35.30.00-E-ICD Implemented version in the control software is rev D but the only change in rev E is addition of a monitor point of the firmware version.	REMOVED
FTS (for LO2 and FLOOG)	ALMA-55.07.00.00-70.35.30.00-C-ICD	LO2 REMOVED
PSA and PSD	ALMA-57.03.000.00-70.35.30.00-C-ICD Implemented version in the control software is rev B, and difference between revs B and C do look significant.	REPLACE by new power supply M&C
DGCK	ALMA-53.04.00.00-70.35.30.00-B-ICD	REPLACE by new DGCK
DTX	ALMA-53.08.00.00-70.35.30.00-B-ICD	REPLACE by new digitiser/IFSwitch and DTX (may be common ICD with DRX)
DRX (BLC)	ALMA-53.06.00.00-70.35.30.00-C-ICD Rev C is what is implemented in the control software and the CRE for it was approved, but the official ICD entry in EDM is still for rev B: ALMA-53.06.00.00-70.35.30.00-B-ICD	REPLACE by new DRX (may be common ICD with DTX)
DTSR (ACAC)	CORL-62.00.00.00.007-A-PLA The control software references this protocol plan document. Officially the ICD document is presumably one for the ACA as a whole: ALMA-62.00.00.00-70.42.00.00-A-ICD	REMOVED
FOAD (not actually used)	ALMA-54.05.00.00-70.35.30.00-A-ICD	REPLACE by new optical hardware M&C if required

2.8.4 Devices that will not have replacements (IFProc, LO2, DTSR)

The ALMA 2030 system will utilise a single LO down-conversion, with all IF conditioning prior to digitisation happening within the digitiser assembly (whether the new IF Switch is also contained within this assembly or remains a separate assembly is currently to be confirmed. See section 2.3 for further discussion). The LO2 related assemblies will no longer exist. However, the IF power control via attenuators that is currently implemented in the IFProc will have an equivalent in the new digitiser module. The LO offsetting currently implemented in the LO2s will move to the “first F” of the DSP, which if implemented in the DTS will require M&C from the control software as part of the DTX/DRX. A ”first F” implemented in the DTS would also require extra M&C and inter-subsystem communication of total digital IF power and scaling factors that would need to be known for quantisation corrections in the correlator subsystem.

Assuming the ACA correlator is decommissioned and the ALMA 2030 role of the ACA is handled by the new ALMA 2030 correlator, there will be no separate DTS receiver for a second correlator.

2.8.5 Interface requirements between BE and Site

The DTS for the ALMA 2030 is described in section 2.4, and the current ICDs summarized as below will be updated, including requirements of communication infrastructure in the whole observatory. In addition, given BE auxiliaries are deployed with the 2nd generation correlator in the OSF, a new ICD between BE and OSF will be required.

ICD	ALMA 2030
ICD between Site and AOS external fibre system (between antenna pads and AOS-TB) ALMA-20.07.00.00-54.09.03.00-A-ICD	REPLACE by new DTS, including new AOS-OSF Fibre Link for DTS and computing (see 2.3.3)
ICD between Computing and Site (AOS-OSF Fiber Optic Link) ALMA-20.07.01.00-70.02.00.00-A-ICD	REMOVED
ICD between DTS and Fiber Optic Transmission Sub-Systems BEND-53.00.00.00-54.00.00.00-A-ICD	REPLACE by new DTS (BE internal ICD)
ICD between AOS-TB and BE Central Equipment ALMA-20.01.02.00-50.00.00.00-A-ICD	REPLACE by new DTS REMOVE FOAD racks
ICD between BackEnd and AOS Computing Communication Equipment ALMA-50.00.00.00-70.02.00.20-A-ICD	REPLACE by new DTS

2.8.6 Interface requirements between BE and Antenna

The mechanical interface, the electric power interface, the electronic signal interface, and the thermal interface between the BE subsystems and the Antenna subsystem will maintain the current requirements [RD22]; especially, the power dissipation from the BE analogue and digital racks where new DGCK, new DTS, and other BE auxiliaries will be mounted shall not exceed 2 kW in total.

Regarding the optical signal interface between the BE subsystems and the Antenna subsystem, a replacement of the existing optical fibres will not be required because the existing 8-fibre cables between the receiver cabin and the antenna pad will be capable to transmit signals required in ALMA 2030 (section 2.4). In addition, connections in the splice boxes located in the antennas and the antenna pads (SB, SB1, SB2, SB4 of Figure 14) will be modified as required by a design of the new DTS.

The communication interfaces and cables running in the BE racks and the receiver cabin will be replaced as needed (see 2.1.1 and Appendix B). The ICDs summarized as below will be updated if a new communication interface is adopted in the ALMA 2030.

ICD	ALMA 2030
ICD between Antenna Subsystem and Back End Subsystems ALMA-34.00.00.00-50.00.00.00-D-ICD	**REPLACE by new communication interfaces as needed (see 2.1.1)**
ICD between Back End Digital Antenna Racks and Computing Hardware & Interfaces ALMA-57.02.01.00-70.02.00.10-B-ICD	**REPLACE by new communication interfaces as needed (see 2.1.1)**

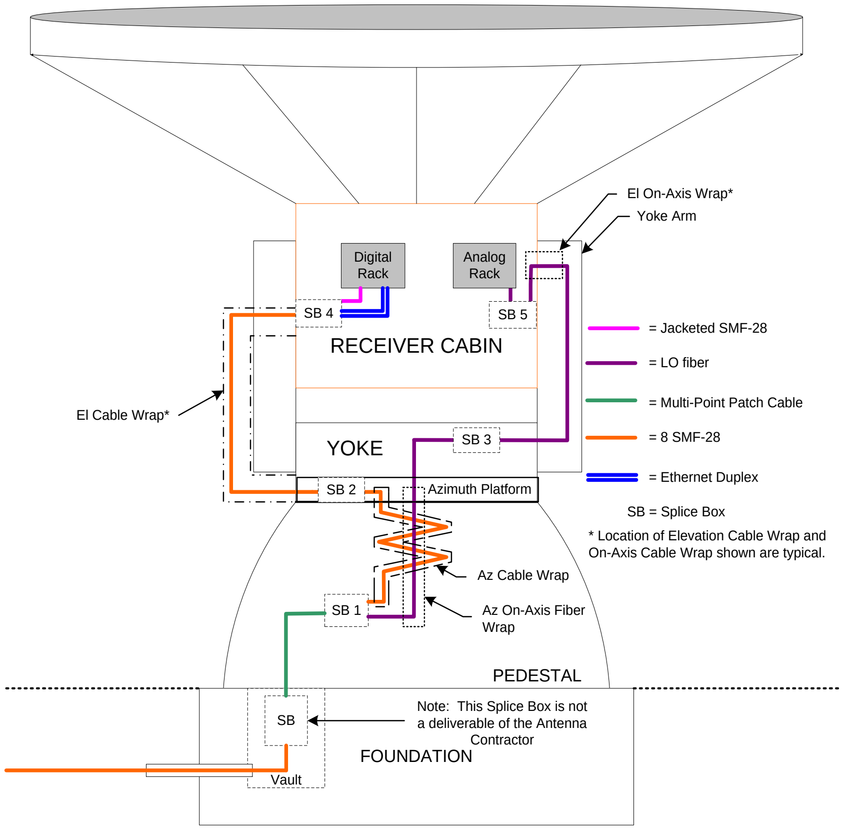


Figure 14: Optical Fibre Routing in Antenna [RD22]

2.9 Charge 8 – Frequency and Timing distribution

Charge description [AD2]:
The working group shall provide an initial assessment on the architecture and requirements related to frequency and timing distribution in the ALMA 2030 System Architecture. The full assessment is out of the scope of the SCWG and will be followed up in studies related to other aspects of the ALMA 2030 planning, such as the implementation of Extended Baselines.

2.9.1 Extended baselines

While the goals of the ALMA 2030 upgrade impact a vast number of systems, the 1st LO Frequency and Timing Distribution (Central LO) is only significantly affected by the Extended Baselines requirement, as all other goals are either currently within technical reach (LO Bands, Tuning ranges, Noise) or do not affect the design of the current system. An ALMA Cycle 7 Development Study ("ALMA Central LO Improvements and Upgrades") is currently under way to develop a technical upgrade roadmap that would allow current and future ALMA Front End receivers to function in antennas that are up to 45 km from the AOS Building (different from an ALMA Baseline). Specifically, it seeks to address the issues of a) the Master Laser Coherence Length, to overcome the degradation of phase information (coherence) passed the 50 % point as it has to travel to the antenna and back, and b) the upgrades required to the current real time Line Length

Correction system, which needs to see both its range increased to accommodate the additional fiber span, and an increase in bandwidth to compensate for the increase time of flight of the Master Laser signal over the increased span. Additionally, an increase in fringe counter resolution and data throughput are being studied, to offer the possibility of an asynchronous correction of the phase delay at the Correlator.

2.9.2 Timing Event TE

The remaining issue is the current Back-end to Correlator Interface, namely getting a 125 MHz (sinewave) reference, the 48ms LVDS Timing Event (TE), and 1 PPS signals to the new Correlator at the OSF, with a first opportunity being offered by the Hardware in the Loop (HiL project), as it also requires the same reference signals to be sent to the OSF.

Should this new Correlator require a different set of references, a technical evaluation will have to be performed once those specifications are known.

The current BE specifications document [RD26], section 5.71, defines the Timing Event (TE / 48 ms) requirements, including jitter, as delivered at each antenna by the Backend subsystem. TE jitter is dependent on the transmission medium used, for LVDS ≤ 0.8 ns is specified while for RS422 ≤ 8 ns. This current performance is not stable enough for time stamping purposes with the proposed ALMA 2030 architecture using an asynchronous DTS.
The jitter for time stamping purposes of the digitized data, assuming an effective sampling rate of 40 GSps, must be better than 25 ps. Achieving this jitter requirement for antenna based oscillators and timing circuits, synchronized to the CLOA, should be feasible considering that the current LO_2 phase jitter, which is phase locked to the 125 MHz reference frequency, already meets a requirement of less than 1 ps (Req. BEND-04522-00/RT [RD26]). The LVDS technology itself is not a limiting factor for this matter since a jitter contribution of less than 1 ps can be achieved.
Once an initial time stamp is set referring the TE when a (sub)-array is created (CSE: clock set event), every DTS has to keep counting the 125-MHz reference without referring TE and has to keep generating time stamps as long as the (sub)-array is active.

Since digitized signals from every antenna are tagged by time stamps before being transported by the DTS, correlators can work asynchronously. The DTS Rx must have a FIFO buffer of sufficient length to absorb TE jitters and DTS delay variations to align data from different antennas by referring time stamps.

2.10 Miscellaneous topics

Although not identified as a specific charge the SCGW is requested in section 2.1 of [AD2]:

The SCWG shall identify and highlight areas of concern regarding requirements that may come up outside of the signal chain that are directly within the scope of this working group. These concerns could include, for example, interference from/to other system components such as antennas and cryogenics, power consumption concerns, etc. These should be raised with other requirements working groups as relevant. In the event that further consultation is needed, the group should feel free to discuss with the ALMA Integrated Engineering Team (IET), Integrated Computing Team (ICT) and Integrated Science Operations Team (ISOpT). The goal shall be to *minimize changes to existing subsystems and infrastructure beyond the part of the system under their consideration, both for cost and operational impact reasons.*

This section summarizes those areas of concern as identified by the SCWG.

2.10.1 Radio Frequency Interference

The issue of RFI has been briefly mentioned in section 3.9.1 of [RD4]. So far ALMA has been in the fortunate position that external interference at its operating frequencies has been practically absent. The only concrete RFI source that ALMA has dealt with so far and resulted in several system measures to be taken was a low earth orbiting satellite, CloudSat, carrying a powerful radar, operating at 94 GHz, for atmospheric research. Unfortunately, the RFI landscape for ALMA will change in the coming years with the advent of 5G mobile telecommunications and worldwide satellite internet access, such as OneWeb. With this forward look to the developing spectrum usage in the mm and sub-mm wavelengths ranges it is strongly advised that appropriate, technical, measures are being taken as an integral part of ALMA 2030.

One mitigation measure to consider is to make the ALMA signal chain resilient to external RFI, e.g. by implementing measures to increase the signal dynamic range but also to consider more advanced options for, automatically, flagging data for the presence of RFI (as noted in 2.2.3.3).

Another category of RFI that must be addressed in the ALMA system architecture for ALMA 2030 is internally generated RFI (“birdies”) due to e.g. local and clock oscillators. Several measures should be taken to minimize the impact of internal RFI. This starts with a system wide frequency planning exercise, e.g. to avoid the LO1 signals fall in the broader IF1 range (YTO leakage), but for the very wide bandwidth receivers of ALMA this cannot solve the issue completely. Active measures to reduce internal RFI, e.g. shielding, 180° phase switching, and frequency off-setting, should be implemented as part of the ALMA 2030 effort.

2.10.2 Reliability of AOS to OSF link to environmental factors

The past few years have highlighted the fragility of the road between the AOS and the OSF to larger-than-planned-for rainfall, as well as soil erosion. It is recommended that any infrastructure improvement plan include civil works to increase drainage and amelioration of the earthworks along the power and fiber cable trenches, as a single event could cripple ALMA Science observations for an extended period of time. A recent example (February 2020) of water induced erosion along the AOS to OSF road is shown below (Figure 15). Should the cable between the AOS and OSF be damaged, ALMA could potentially lose all of its observing capabilities for days.

Figure 15 Exposure of the fiber cable between one antenna pad and the AOS

2.10.3 LO_1 tunability for Band-to-Band phase transfer

Band-to-band (B2B) phase transfer is a key technique to improve performance in submillimeter (>300 GHz: Band 7, 8, 9, and 10) interferometry by calibrating atmospheric excess-path-length fluctuation at high frequency by observing a phase calibrator at a low (below Band 7) frequency. The phase calibrator must be within ~ 4° from the target and the switching cycle (cal-target-cal) should be within ~20s [RD36]. Band 3 to 7 phase transfer is offered since Cycle 7, but higher

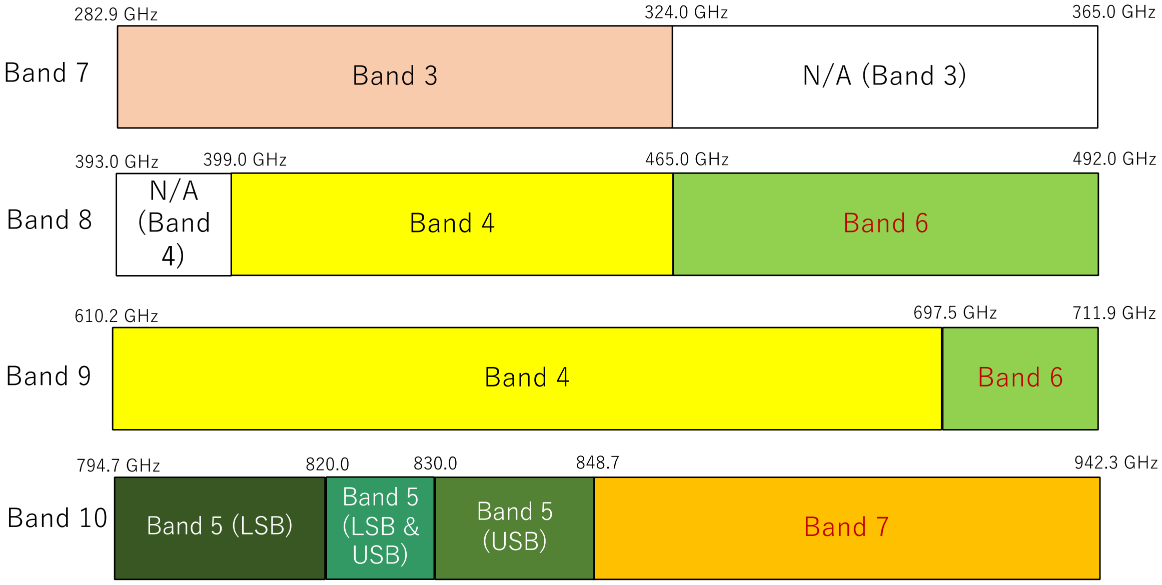


Figure 16: harmonic frequency solutions

bands are under preparation targeting Cycle 9. In ALMA 2030, B2B is more essential to realize submillimeter observations with longer baselines.
Currently, frequency switching in the master laser synthesizer with the pre-tuning capability is prohibited for science observations, primarily because the control software does not recover gracefully from the occasional (but inevitable) failures to relock the photonic LO in this mode. Therefore, harmonic frequency switching (HFS) is required not to change the photonic LO signal. Solutions for HFS are shown in Figure 16 [RD37].
The HFS condition restricts the observing frequencies. Because there is no LO1 solution in 324 - 365 GHz (Band 7) and 393 - 399 GHz (Band 8), current ALMA system doesn't allow B2B in the RF range of 328 - 395 GHz. Wider IF bandwidths (4 - 16 GHz) in ALMA 2030 fills the majority of the LO1 solution gap. However, RF in 343 - 346 GHz remains inapplicable with B2B, assuming IF = 5 - 19 GHz (1 GHz at both edges to be trimmed). Another problem is unavailability for an integer RF frequency ratio that removes 2nπ phase ambiguity to improve phase referencing performance including accuracy in astrometry [RD38].
To fill the gap and allow an integer frequency ratio, the WG suggest two solutions:

1. Enable pre-tuning and fast switching capability of the laser synthesizers to realize non-HFS B2B observations. The phase must remain stable via frequency flip-flop.
2. Extend FLOOG frequency range from current 20 - 45 MHz up to 1 GHz, so that HFS condition fill the gap. This is a contingency for solution 1. Concurrent dual LO1 tuning for low and high bands would yield better phase stability with less control errors. It has been pointed out however that increasing this range impacts the loop bandwidth and will increase the phase noise contributions (from the Laser Synthesizer for example). This also means the YIG assembly has to be redesigned, and will require coarse tuning as well.

As option 1 is more straightforward to implement (via software and firmware changes) than option 2 (which will require a significant redesign of the WCA, its YIG, PLL, and coarse tuning circuits), it is therefore the preferred recommended solution.

2.10.4 Cosmic radiation impact on microelectronics

Triggered by a statement in [RD27] that the expected MTBF (Mean Time Between Failures) due to SEU (Single Event Upset) for a DSP/OT board at the ALMA location is 224 hours a further assessment of susceptibility to cosmic radiation for those sub-systems that use large number of FPGAs is advised. Note that this MTBF prediction is based on the assumption that 264 Intel FPGA Stratix 10 TX 1ST110-SF50 devices are being used. It is not specified if the number assumes operation at the OSF or AOS site.

Although predicting the susceptibility of semiconductor devices is a complex matter dependent on factors like device technology, manufacturing process, and operating bias there is a trend that higher density integrated circuits using smaller transistor features will lead to an increased susceptibility. Having this in mind it is noted that the current ALMA Correlator is based on ASICs designed in CMOS 0.25 micron technology. The Tuneable Filter Banks uses 90 nm FPGAs devices. The FPGAs considered for ALMA 2030 are based on 14 nm technology.

Altitude of operation also impacts the susceptibility of microelectronics to cosmic radiation (see Table 4).

Table 4 relative neutron flux at ALMA and SKA Mid sites

Location	Latitude	Longitude	Elevation	Relative flux[3]
ALMA OSF (CL)	23.07275S	67.98090W	2900 m	4.88
ALMA AOS (CL)	23.02357S	67.75367W	5100 m	15.64
SKA Mid / Karoo (SA)	30.75337S	21.43139E	1100 m	2.10

2.10.5 Product lifecycle / lifetime

From the ongoing study and development activities towards ALMA 2030 it is clear that technology is developing very fast, especially in the areas of electronics and information technology improvements in performance with orders of magnitude are being noticed since the conception of ALMA. Just two examples where ALMA 2030 will benefit from this trend is in the area of digital signal processing, e.g. correlator, due to advances in microelectronics and, optical, data transmission which is beneficial to the Digital Transmission System. This very fast technology development is also driven to a large extent by market needs, e.g the Internet and, mobile, communications, and this results that more high performance commercial of the shelf products are available for the ALMA 2030 upgrade.

Unfortunately the downside of this innovation is that the product lifetime of, especially COTS, products become similar or often less compared to the minimum lifetime requirements of ALMA products.

One example to illustrate the issue is the lifetime of FPGAs, [RD40] suggests that Altera FPGAs have a lifecycle of 15+ years. This number should be compared with the minimum lifetime requirement of ALMA sub-systems of 15 years in which these devices are used, e.g. correlator. This simple example illustrates that an active product / component obsolescence management is necessary and should already start in the design phase, e.g. with the selection of components.

2.10.6 Orphaned Products

In executing our charges we have noticed that it is not always clear who will be responsible for a certain activity or deliverable within the ALMA 2030 upgrade project. Some examples to illustrate this finding are the new IF Switch (see section 2.3.4) and the provision/renovation of a room, with HVAC, suitable for the 2nd Generation Correlator.

If these items are not systematically identified, e.g. with the support of product and work breakdown structures, there is a risk that these get overlooked.

---

[3] relative to the sea-level flux in New York City, New York, USA. This point has historically been the reference point for neutron flux measurements. Values calculated based on the on-line tool available at http://www.seutest.com/cgi-bin/FluxCalculator.cgi

3 ALMA 2030 Prototyping and Deployment

Although not defined as a specific charge to the SCWG in [AD2] it is requested to address options for a prototyping and deployment framework that minimizes ALMA science observing downtime, while not unduly prolonging the time to deliver new capabilities. In this chapter we present these options which will be the subject of programmatic assessment by ALMA after the completion of the WG report, and considering the implications on the full ALMA system from antennas to archive.

3.1 Prototyping assessment

Our general objective for prototyping is mainly to de-risk technological uncertainties for a new product under development. Normally prototyping is done before the detailed design of a product commences, often as part of the preliminary design phase [RD33]. We emphasize that developing prototype products and their validation is commonly a very resource intensive activity. A prototyping activity can only be justified if it retires a major technical risk. Where feasible other options, e.g. modelling and simulation, should be considered as a, resource efficient, alternative.
With this strategy in mind, we propose the following prototyping activities to be considered.

3.1.1 Asynchronous DTS

The move from the currently synchronous, custom designed, DTS to an asynchronous solution based on COTS products is likely to be one the largest hardware changes to the ALMA system architecture leading to ALMA 2030. DTS data rates from a single antenna to the central correlator will increase from the current 120 Gb/s to as much as 1,600 Gb/s while for all antennas being part of the array coherence shall be maintained. In practice this means for the ALMA 2030 system architecture that digitized data must be time stamped at the antenna with a resolution better than 25 ps (assuming an effective sampling rate of 40 GSps) and this resolution shall be resolved at the input to the correlator. This under impairing conditions due to e.g. clock jitter and variable delay in the DTS which is likely different for each antenna.
Considering this major change to existing architecture and the technological challenges of the high data rates we are of the opinion that an asynchronous DTS including those products interfacing with it need to be demonstrated at system level. Despite the substantial resource and time needed we see this as an efficient way to retire the following technical risks:

- Astronomical data transport via asynchronous DTS without impairing coherence;
- Proof of design concept integrated in ALMA 2030 system architecture;
- Distribution of clock signals across the array with sufficiently low jitter;
- Uncertainties in interfaces between sub-systems.

3.1.1.1 Products to be prototyped

The technology solutions studied for Digitizers, the related clock generation and analogue IF signal selection / conditioning, Digital Transmission System, and supporting Digital Signal Processing [RD27] shall be developed towards prototype products that at least:

a) shall match the architecture of the new 2nd Gen Correlator architecture [RD1];

b) should match the performance of the ALMA 2030 goals [RD2];
c) are sufficiently mature to be used in a system demonstration (see section 3.1.1.2 below).

As an integral part of this prototype design phase appropriate verification plans and procedures shall be established that allow an unambiguous and efficient assessment of the performance of the products designed.

3.1.1.2 Prototype system demonstration

The main objective of this System Demonstration shall be to prove that the developed prototype products are able to perform and operate as required in a system architecture equivalent to the one foreseen for ALMA 2030. The System Demonstration is expected to be an important means to reduce risks in the subsequent product life-cycle phases, especially those for product design.
For this purpose it is expected that the System Demonstration shall mimic an interferometer configuration with not less than two elements. It is not expected that all sub-systems of the ALMA 2030 interferometer architecture are built. Where appropriate, technically representative alternatives, functional models, might be used in the form of simulation models or simplified test sub-systems. As an example, two options are provided for the System Demonstration environment:

i. *OSF test set-up*: for this configuration two ALMA antennas might be used in which the prototype digitizers are integrated and the prototype DTS transports the digitized data to a test correlator. This two-element interferometer would allow observation of astronomical sources. For convenience sake the test configuration is installed at the JAO Operations Support Facility making use of existing infrastructure where feasible. In this respect also the use of the Hardware in the Loop System Environment (HILSE) should be considered.
ii. *2nd Gen Correlator test set-up*: For this configuration the prototype digitizers and prototype DTS products are connected to a, prototype, 2nd Gen correlator without using a full front-end mounted in an antenna. The prototype digitizers could be connected to a common noise source mimicking the astronomical signal. By varying the differential delay between the noise signals to the digitizer inputs tracking of an astronomical source could be simulated.

It is emphasized that these are just two suggestions to be considered, alternatives should be reviewed by those groups responsible for the relevant ALMA 2030 sub-systems, in collaboration with the AMT.

3.1.2 Integration and Interface verification

Despite the availability of contemporary advanced simulation and modelling tools it can be still efficient, in terms of resources and time, to prototype complex components to verify compliance to interfaces requirements and perform actual integration of prototype products which are similar in form, function, and performance to the final design in the product design phase. This type of integration and interface verification is mainly foreseen at sub-system level. Since form, function, and performance of the prototypes should be similar to the final design it is expected that this integration and interface verification is part of the detailed design phase.

3.1.2.1 FE Assembly IF processor / Digitizer

As advocated in section 2.3 the new digitizers and supporting functions for level detection should be integrated inside an IF switch capable of handling the increased IF bandwidth.

It is proposed that a prototype IF switch is designed and built for integration inside the FE Assembly. Such an activity would mitigate several risks in the manufacturing and integration phases of this product:

- Retire, mechanical and electrical, interface non-compliances;
- EMC issues;
- Minimize integration issues of the new IF switch during the full roll-out in the field.

3.1.3 Front End receiver cartridges

Development of new Front End receiver cartridges will also proceed through a prototype phase to ensure that the new ALMA 2030 performance requirements are met. It is expected that any new cold cartridge assembly (CCA) and warm cartridge assembly (WCA) will be designed to interface mechanically, optically, thermally, and electrically into the existing Front End cryostat. However, as described by the recently-proposed development project, “Band 6v2 Receiver Upgrade: Phase 1”, the verification of a prototype (or pre-production) cartridge on the sky at the ALMA site will likely require some modifications to the ALMA control software. Such modifications will be needed to support any new hardware characteristics before the new cartridge can be operated successfully on an antenna. An example of a new hardware characteristic is a strategic increase in the fundamental frequency of the YIG oscillator in the WCA in order to avoid having this strong signal present in the expanded IF range of the receiver. Such a change would mean that the LO multiplication factor for that Band on that specific antenna needs to be correspondingly smaller, which requires the addition of per-antenna entries in the TMCDB for that quantity. Despite the added complications entailed, the ability to perform such on-site tests will be essential to retire any other unforeseen risks with the wider band IF ranges.

Depending on the relative timing of the new digitizer and the prototype receiver cartridge, the testing of a wider IF receiver cartridge could be considered in two stages. In the first stage, when the faster digitizer is not yet available, the new receiver cartridge could (in theory) be tested over the current 4-12 GHz IF range by using the current digitization of four 2 GHz basebands, one sideband at a time. To achieve this configuration, the current software tuning restrictions that limit the 2SB receiver IF range to the current range of 4-8 GHz (or 4.5-10 GHz in the case of Band 6) would need to be temporarily removed. In the second stage, when the faster digitizer is available, testing the upper portion of the IF range (e.g., 12-16 or 12-20 GHz) could proceed.

3.2 Deployment

Deployment of new hardware and software products that enable the ALMA 2030 requirements will be a major challenge for all stakeholders involved. The message from the ALMA Director, reiterated in the SCWG Charter, is to keep the Observatory operational and deliver its data to the astronomical user community while the ALMA 2030 upgrade activities are executed in parallel. Observatory down-time, if unavoidable, to roll-out ALMA 2030 products must be minimized, this down-time rather be limited to less than a few months instead of years.
Although no concrete schedule date on the various ALMA 2030 upgrade project is available to the SCWG we have developed an overall strawman schedule that at least allows an assessment of two different deployment strategies, one based on an almost full parallel deployment of upgrade equipment while continuing observations, and a second one based on a scenario where the

correlator remains located at the AOS building. The latter means that before installing a new 2nd Gen Correlator the current correlator first needs to be removed.

Comparing these two scenarios already provide a good insight in the amount of observatory down-time they would require and the constraints and conditions that have to be considered to implement these scenarios.

The task split and duration of the individual upgrade projects are based on experience from similar projects, e.g. from the ALMA Construction project.

3.2.1 Assumptions & Conditions

While products fitted in one of the 66 array elements can be gradually upgraded without completely stopping the observatory this is not feasible for unique, core sub-systems like the correlator. In section 3.2.2 below we consider two extreme deployment scenarios to illustrate the expected Observatory down-time.

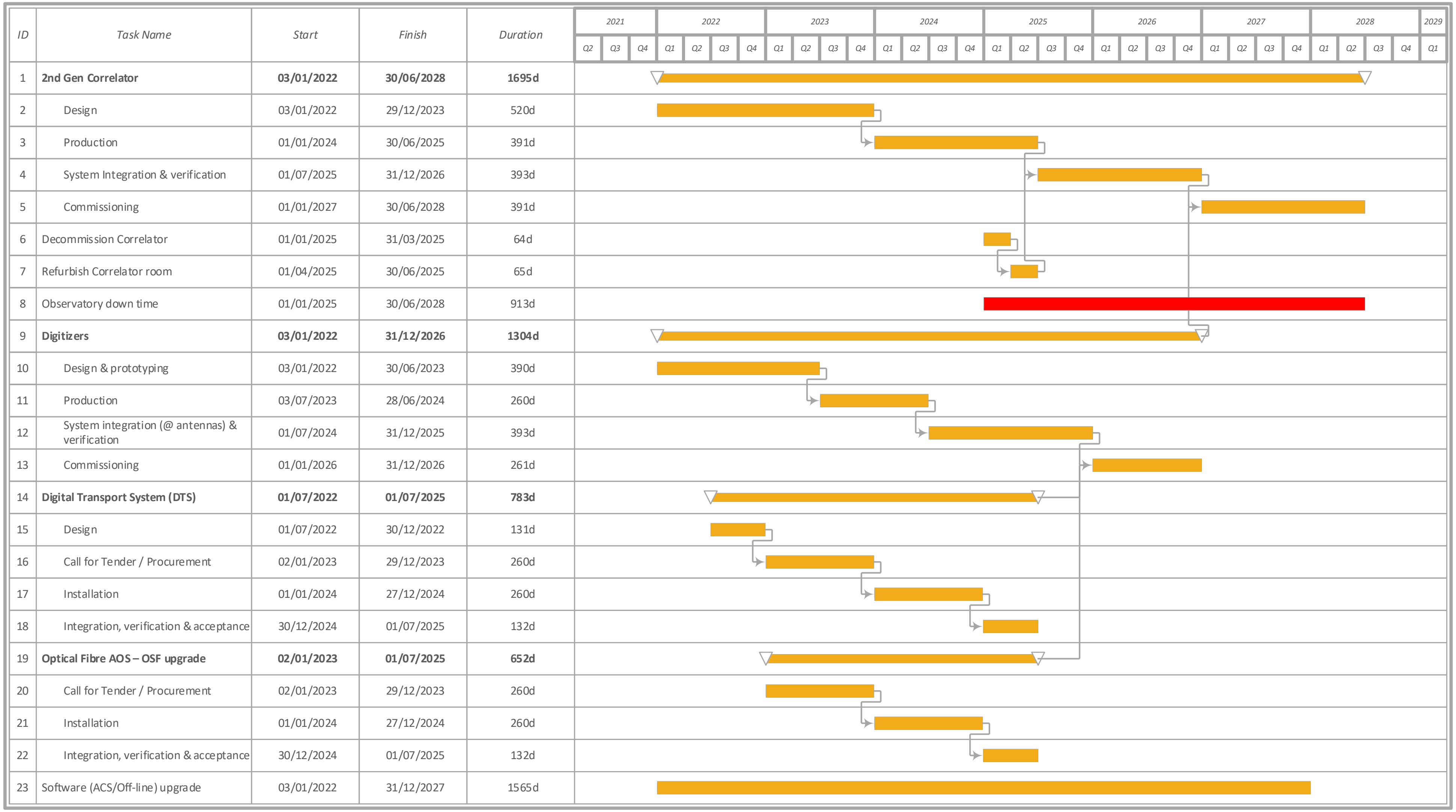
The feasibility of these deployment scenarios depend on technical, e.g. electrical power supply, and programmatic conditions, e.g. availability of staff and funding.

3.2.2 Strawman schedules

Making the assumption that the 2nd Gen Correlator would be installed at the location of the current correlator, inside the AOS Technical Building, a substantial time will be needed to decommission the current equipment before the hardware upgrade can be installed. This scenario is presented in the Gantt chart shown in Figure 17. As can be seen in this Gantt chart the Observatory will not be able to deliver astronomical data, due to the absence of a correlator, for an extended time, possibly 2 to 3 years, which would be untenable for ongoing observatory science. The benefit of this scenario is primarily limited to avoiding the need for a new correlator room.

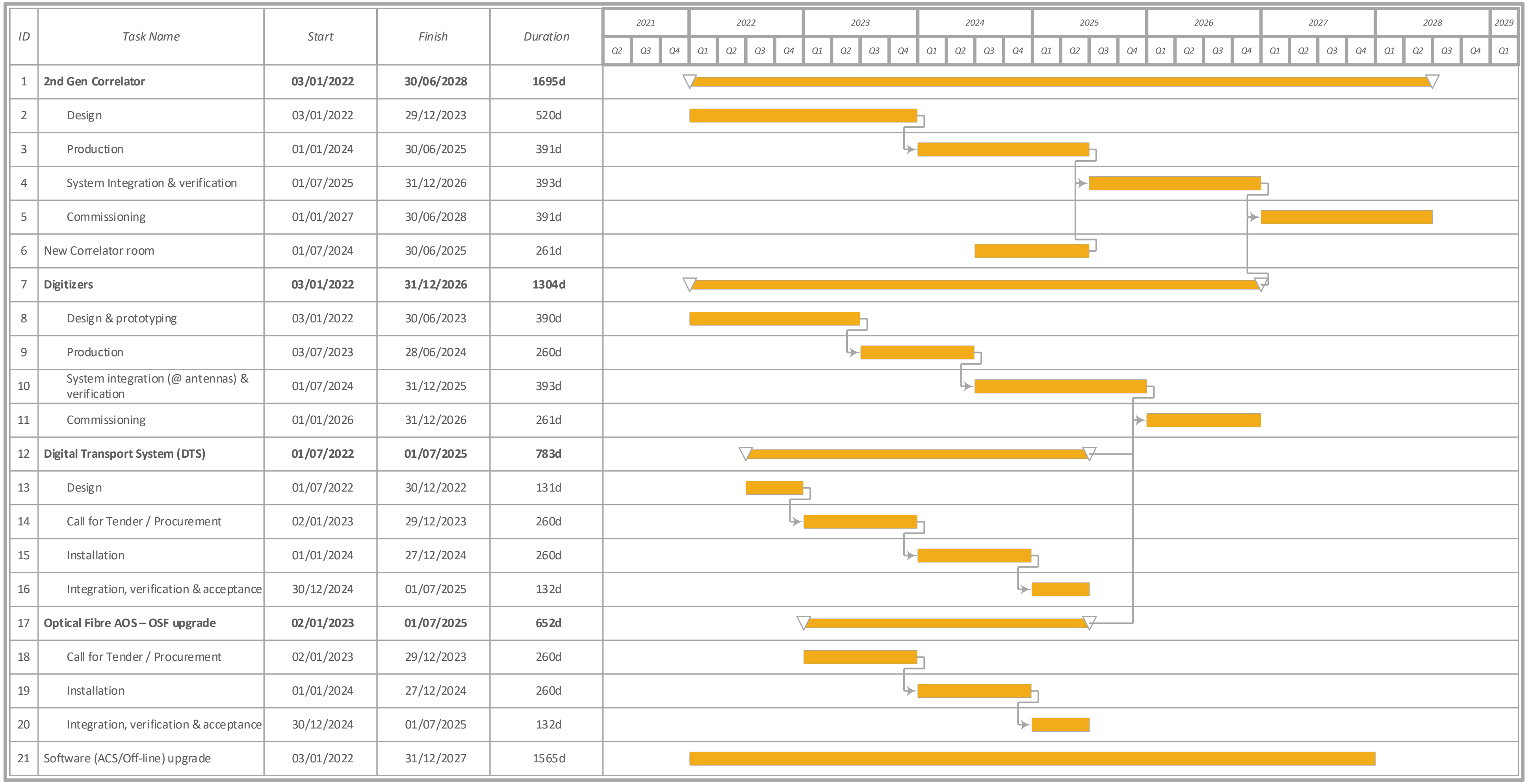
An alternative deployment scenario is depicted in Figure 18 in which case the new correlator is installed while the Observatory continues its normal operations delivering astronomical data with the old digitizer and old correlator. When the following key conditions are met, a seamless transition or even parallel operation, but not simultaneously, of the current and ALMA 2030 system configurations should be feasible:

- 2nd Gen Correlator located in a new room, e.g. as proposed in section 2.7.2;
- Use of 2nd gas turbine to provide the increased electrical power draw during the transition phase (see section 2.7.1 for details);
- Use of new IF switches in each FE-assembly that allow routing the IF signals into the current Analog Backend or the new ALMA 2030 backend (see section 2.3.4).



ID	Task Name	Start	Finish	Duration
1	**2nd Gen Correlator**	**03/01/2022**	**30/06/2028**	**1695d**
2	Design	03/01/2022	29/12/2023	520d
3	Production	01/01/2024	30/06/2025	391d
4	System Integration & verification	01/07/2025	31/12/2026	393d
5	Commissioning	01/01/2027	30/06/2028	391d
6	Decommission Correlator	01/01/2025	31/03/2025	64d
7	Refurbish Correlator room	01/04/2025	30/06/2025	65d
8	Observatory down time	01/01/2025	30/06/2028	913d
9	**Digitizers**	**03/01/2022**	**31/12/2026**	**1304d**
10	Design & prototyping	03/01/2022	30/06/2023	390d
11	Production	03/07/2023	28/06/2024	260d
12	System integration (@ antennas) & verification	01/07/2024	31/12/2025	393d
13	Commissioning	01/01/2026	31/12/2026	261d
14	**Digital Transport System (DTS)**	**01/07/2022**	**01/07/2025**	**783d**
15	Design	01/07/2022	30/12/2022	131d
16	Call for Tender / Procurement	02/01/2023	29/12/2023	260d
17	Installation	01/01/2024	27/12/2024	260d
18	Integration, verification & acceptance	30/12/2024	01/07/2025	132d
19	**Optical Fibre AOS – OSF upgrade**	**02/01/2023**	**01/07/2025**	**652d**
20	Call for Tender / Procurement	02/01/2023	29/12/2023	260d
21	Installation	01/01/2024	27/12/2024	260d
22	Integration, verification & acceptance	30/12/2024	01/07/2025	132d
23	Software (ACS/Off-line) upgrade	03/01/2022	31/12/2027	1565d

Figure 17 Schedule assuming sequential deployment of correlator



ID	Task Name	Start	Finish	Duration
1	**2nd Gen Correlator**	**03/01/2022**	**30/06/2028**	**1695d**
2	Design	03/01/2022	29/12/2023	520d
3	Production	01/01/2024	30/06/2025	391d
4	System Integration & verification	01/07/2025	31/12/2026	393d
5	Commissioning	01/01/2027	30/06/2028	391d
6	New Correlator room	01/07/2024	30/06/2025	261d
7	**Digitizers**	**03/01/2022**	**31/12/2026**	**1304d**
8	Design & prototyping	03/01/2022	30/06/2023	390d
9	Production	03/07/2023	28/06/2024	260d
10	System integration (@ antennas) & verification	01/07/2024	31/12/2025	393d
11	Commissioning	01/01/2026	31/12/2026	261d
12	**Digital Transport System (DTS)**	**01/07/2022**	**01/07/2025**	**783d**
13	Design	01/07/2022	30/12/2022	131d
14	Call for Tender / Procurement	02/01/2023	29/12/2023	260d
15	Installation	01/01/2024	27/12/2024	260d
16	Integration, verification & acceptance	30/12/2024	01/07/2025	132d
17	**Optical Fibre AOS – OSF upgrade**	**02/01/2023**	**01/07/2025**	**652d**
18	Call for Tender / Procurement	02/01/2023	29/12/2023	260d
19	Installation	01/01/2024	27/12/2024	260d
20	Integration, verification & acceptance	30/12/2024	01/07/2025	132d
21	Software (ACS/Off-line) upgrade	03/01/2022	31/12/2027	1565d

Figure 18 Schedule assuming parallel correlator deployment

4 ALMA 2nd Generation Correlator Proposal

By the time that the first draft of this Final SCWG report was originally due, 1 August 2021, information about the 2nd Generation Correlator proposal was kindly made available by the NA Executive. Since this new correlator is a major sub-system to which the signal chain must interface with, it was agreed with ALMA management to expand this report and take into account the information made available to the SCWG.

The SCWG hasn't received the full proposal for the 2nd Gen Correlator as selected by the NA Executive, information has been limited to a primer [RD42] and a memo [RD43] presenting some options on how the proposed correlator could be integrated in the ALMA system architecture.
Since the design of the proposed 2nd Generation Correlator, as constrained by the current proposal cost-cap to a 2x bandwidth configuration, partially deviates from the recommendations of the different working groups [RD1][RD2][RD4], its system integration needs a revised view from what has been advocated so far. To avoid confusion to the reader the integration of the proposed 2nd Generation Correlator is addressed in this dedicated Chapter 4. Other parts of this report, especially Chapters 2 and 3 have been written on the basis of an optimized top-down system approach, compliant with the recommendations in [AD1][RD1][RD2][RD4], without considering the constraints of the 2nd Gen Correlator proposal.

In summary, there are several architecture options based on the original 2nd Generation Correlator proposal. The ones with least risk but possibly additional costs that provide the most science flexibility and throughput for an initial, 2x bandwidth, configuration require an FFX architecture (taking note of the definition of "first F" as addressed in section 2.6.1) that might physically be distributed among (up to) three locations, antennas at the AOS, AOS Building, and OSF Building. However, possible modifications to the proposed design options have been researched by the proposing team and discussed, and a promising option that does not require a "first F" has been recently identified. Regardless of whether a "first F" option is ultimately chosen, the TALON-DX board, originally designed for the SKA Mid correlator, is currently limited to 100 GbE fiber ingest, which sets a constraint on the attributes of the signals that the ALMA2030 data transport system shall deliver to the correlator.

A preliminary analysis of a correlator architecture that includes a "first F" at the antennas and uses 100 Gb/s fiber inputs is provided in the sections below, structured by the SCWG charges.

4.1 Charge 1 – Software Operating Environment

There is some concern about added complexity to control those correlator parts mounted at antennas and possibly the AOS Building. Verification and commissioning of a distributed correlator sub-system might be more complex compared to having the correlator in a single location. But as noted in section 2.6.1, if the initial coarse channelization produces fixed-tuned sub-bands and LO-offsetting / phase switching in the "first F", then the complexity is reduced. No major risk, still simplification compared to current system.
Additional communication paths for digital total power measures, scaling factors or other parameters will likely be needed to allow corrections at the end of the correlation process (quantisation correction, sub-band stitching).

4.2 Charge 2 – Backend

Recognizing that this charge is limited to BE product 52 - IF Processor Sub-subsystem (IFPS), see section 2.3, no difference is expected for a configuration using the NA 2nd Gen Correlator compared to the original concept.

4.3 Charge 3 – Data Transmission System

At time of writing, potentially locating the "1st F/coarse channelization" at the antennas, as well as the ingress limitations of the current generation TALON-DX board (100 Gb/s maximum per fiber input) has a major impact on the DTS system, and the hardware that needs to be developed, tested and delivered to the ALMA2030 project, including which group will be assigned and financed to deliver what hardware. As the UBordeaux LAB development work and the NRC AT.CSP proposal were developed separately, there are currently interfacing issues.

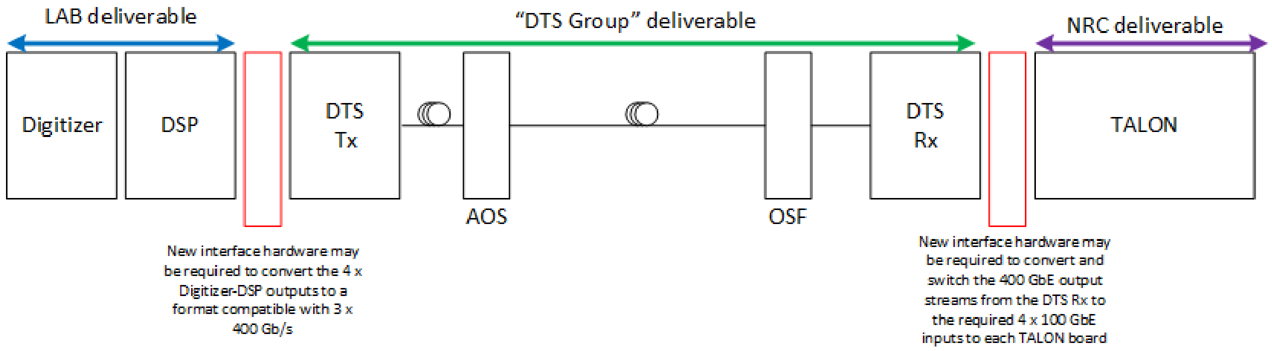


Figure 19 Diagram of three major deliverable components of the ALMA2030 digital system.

One option being considered to allow these different groups to avoid having to significantly customize or upgrade their proposals is to add an "interface box" at each end, to route/multiplex/demultiplex the individual 400 GbE data streams into multiple 100 GbE streams and vice-versa, upstream of the Antenna optical layer, and downstream of the Correlator receiver. The core DTS optical transmission layer could then be optimized for simplicity and cost, and the risks and additional resources needed to heavily customize a newer TALON board would be greatly reduced. While difficult to define at this time, it may be as simple as, for example, a configurable software driven 100G/400G Ethernet Fabric Switch (belonging to the industry dubbed "Leaf and Spine" family of products) at the Digitizer output and TALON Ingest boundary. If such is the case, it would add about US$ 10,000 to the cost of each antenna DTS system, or US$660,000 to US$ 700,000 overall.

If a COTS solution is not available, another option would be to design the DTS system with additional interface boards (similar to the ones in the LAB proposal) that use FPGAs capable of 400GbE/100GbE input/output conversions. These boards, with suitably specified FPGAs, could even take over the station-based processing of the correlator, reducing the number of TALON units required and spreading the correlator/DSP costs over two projects. The potential cost savings to the correlator project from not needing TALON units for station-based processing might go some way towards providing more TALON units for correlation bandwidth. However, as this system optimisation has a lower state of readiness, and involves very close collaboration between two projects and the correlator software developers, there would be more timeline uncertainty and potential unanticipated costs and effort compared to using the already designed TALON units for the station-based processing. It should be remembered, however, that the Baseline correlator was the result of just such a collaboration, with the TFBs (providing much of the station-based processing co-located with the correlator but without the DTS in between) provided by a different group from the rest of the correlator, and it was highly successful.

4.4 Charge 5 – Data Transport Format

Assuming that the data transport will remain Ethernet packet-based rather than a custom protocol, no significant changes are expected to what was presented in section 2.6. Unless a definite need for a custom protocol arises, the use of plain Ethernet is strongly preferred. Regarding the single dish VLBI use case, while the data will ultimately be written in VDIF format, the conversion to this format could occur either before data transport, after data transport, or output from the correlator (as recommended in section 2.5). An alternative option is for an FPGA on the DTS receiver board at the OSF to perform the conversion to VDIF.

4.5 Charge 6 – System

Electrical power consumption and room space needs to be reconsidered for the various configuration options of the 2nd Gen Correlator. This is probably less of an issue for antenna-based equipment but if equipment is installed at the AOS Building this needs to be carefully reviewed, not only for the final configuration but especially during the transition phase from current system to ALMA 2030. One should keep in mind that the current system must be kept operational as long as the ALMA 2030 one is not available.
It still needs confirmation that a 2nd Gen Correlator capable of processing the stretch bandwidth goal, 16 GHz / 4x current bandwidthis compliant with the electrical power allocation.

There is some concern about reduced correlator efficiency due to complexity of the digital signal chain with the correlator physically distributed among multiple boards, e.g. with a first F at the antenna, with truncation and requantization steps (processing stages prior to the DTS might have to requantize their output to the limited DTS word size). It is recommended that the overall correlator efficiency is analysed for the various configurations and taken into account in a trade-off as part of the down-selection of the preferred 2nd Gen Correlator sub-system configuration.

4.6 Charge 7 – Interfaces

As a general statement it is emphasized that splitting up the correlator sub-system into multiple components allocated to different groups responsible for design and production increases technical and programmatic risks. To facilitate ALMA2030, a system integration of the prototype DG, DTS, and Correlator (including control software) will need to happen, likely somewhere in the northern hemisphere, regardless of how the functionality is partitioned and this should mitigate the aforementioned risks.

ACA TP Spectrometer interfacing: If the 2nd Generation correlator will not be used for total power observations (i.e., those normally obtained with the PM antennas), then the correlator architecture will impact the design of the upgrade to the ACA Spectrometer (ACAS). Specifically, if an initial coarse channelization is performed upstream of the correlator, then for simplicity of operation the upgraded ACAS will also need to accept the data streams produced by the channelization. ACAS itself is a software correlator and quite flexible to expand its capabilities to accommodate new requirements. So it is expected that a coarse channelization will not be a problem.

4.7 Charge 8 – Frequency and Timing distribution

No substantial changes to what is presented in section 2.9 are expected for a configuration using the NA 2nd Gen Correlator compared to the original concept. When part of the correlator sub-system is installed at the central AOS Building the clock of that part might need to be synchronized with the correlator equipment located at the OSF. Still the timing requirements for the correlator subsystem are expected to be modest since the ingress is time-stamped data transported by an asynchronous DTS. PTP / IEEE-1588 should be a standard, commercial solution providing accurate timing information, uncertainty less than 1 μs, at any correlator equipment that might be installed at the AOS Building.

4.8 Miscellaneous topics

No additional, major issues to what has been presented in section 2.10 could be identified for a system configuration based on the NA 2nd Gen Correlator proposal.

5 Consolidated Conclusions and Recommendations

Based on the analysis presented in chapter 2, Technical Charges and their Analyses, and the assessment in chapter 3, ALMA 2030 Prototyping and Deployment, conclusions and recommendations are made to each of the specific charges identified in the SCWG Charter [AD2].

5.1 Working Group Charges

5.1.1 Charge 1 – Software Operating Environment

The requirements considered for this charge are primarily the cross section between the signal chain sub-systems relevant to the SCWG, back-end and DTS, and the ALMA Control Software. Roughly speaking this cross-section consists of two sets of requirements categories a) interface related and b) operational related. Final, detailed requirements for the software operating environment can only be made as part of the preliminary design of the relevant equipment when specific choices are made on design concepts and architectures.
We have addressed the following key aspects:

- Communication interfaces with new equipment
    - The SCWG recommends to adopt an Ethernet based system to replace the current CAN-bus for monitor & control of new equipment.
- Protocols
    - The SCWG recommends to use industry standards for M&C communication protocols in interfacing with equipment, e.g. TCP/IP and OPC Unified Architecture (OPC UA). By abandoning the ALMA specific implementation of the CAN-bus the TE signal will no longer be available on that bus. The TE signal could be replaced by either NTP or PTP depending on the timing accuracy needed.
- Impacted software components
    - The following software sub-systems will be affected when implementing ALMA 2030:
        - Common software to online and offline
        - Online subsystems (excluding correlator): Control, SSR, and TelCal
        - Offline components:
            - Observing Tool
            - ALMA Sensitivity Calculator
            - Pipeline
            - Archive
            - Calibrator database and flux density service
            - Scheduler
            - CASA
    - The corresponding software documentation for the listed components needs to be updated, which is an effort that shouldn't be underestimated.

5.1.2 Charge 2 – Backend

BE product 52 – IF Processor Sub-subsystem (IFPS) is the main topic of this charge. The SCWG supports the signal chain architecture, a single heterodyne stage instead of the current double frequency conversion, as recommended by the ALMA Frontend & Digitizer Specification Working Group. Considering this choice the SCWG recommends:

- To replace the current IF Switch inside the FE-Assembly by a newly designed unit that exhibits the following features:
    - Has the digitizer integrated to avoid the lossy, frequency dependent, coaxial cable currently connecting FE-Assembly to the analogue Back-end rack;
    - Supports an IF input bandwidth that matches the 1st Nyquist zone of a 40 GSps digitizer, taking into account any alias filter response ahead of the digitizer, and accommodating the IF ranges of the different receivers;
    - Has a step attenuator providing sufficient range to cover the IF power level variations, and accommodates both the new and legacy receiver bands;
    - Provides analogue power detectors, wide- and narrow-band, replacing the detectors currently in the analogue Back-end;
    - Provides an analogue IF output to the legacy Back-end sub-system. This output is essential to allow for a transition from current to the new ALMA 2030 system with minimum operational down-time.

5.1.3 Charge 3 – Data Transmission System

Assuming a minimum requirement of 6 bits/sample and a stretch goal of 8 bits/sample, both at a nominal sampling speed of 40 GSps, the SCWG recommends:

- To use COTS hardware instead of a custom design for the DTS. It is explicitly noted that COTS hardware has packet based, asynchronous data transport;
- An actual raw data rate, excluding any overhead, of 960 Gb/s (minimum) and 1280 Gb/s (stretch goal);
- For data transmission hardware the current industry-developed family of 400G CFP2/4 or QSFP-DD Digital Coherent Optics Transceivers. This would allow the entire data stream from each antenna to be carried by a small number (two, three, or four) 400Gb/s system;
- To install a new, dedicated, high fiber count (> 160 fibers) cable between the AOS and OSF, which provides a dedicated signal path between each antenna and the Correlator.

5.1.4 Charge 4 – Digitization Format

The suggested requirements under this charge are directly derived from the recommendations made by the ALMA Frontend & Digitizer Specification Working Group.

- Number of basebands
    - While a coarse channelization at the antenna remains a viable option for ALMA2030, the SCWG endorses the preference that there be a total of four

basebands, comprised of LSB and USB for two, orthogonal, polarizations, will be made available at the input to the Correlator.

- Number of bits
    - The minimum number of bits per data sample to be transported by the DTS to the correlator ingress shall be six. As a stretch goal the SCWG recommends eight bits per sample to accommodate an increased head room due to external RFI.

5.1.5 Charge 5 – Data Transport Format

As a direct consequence of the previous recommendation under charge 4, to use a single baseband per sideband and polarization, the data will be transported as full time series from antennas to correlator.

For the data format of the packetized data transported by the DTS standard, industrial protocols, e.g. Ethernet protocol, are advocated by the SCWG.

5.1.6 Charge 6 – System

Under this broad charge the SCWG addressed the explicit topics summarized below and presents corresponding recommendations:

- Electrical Power
    - A comprehensive analysis of current electrical power consumption at the ALMA Observatory over time and per sub-system has been made.
    - To support the analysis of deployment scenarios of ALMA 2030, the various phases in transitioning from current system to the new system have been assessed.
    - We recommend that the total electrical power consumption of the 2nd Generation Correlator, assuming that it also correlates the signals from the ACA 7m antennas, and the ACA Spectrometer is limited to **265 kW**. This cap includes the electrical power necessary for the HVAC systems to create the environmental conditions to operate this equipment.
- Correlator Location
    - Space requirements for the 2nd Generation Correlator have been estimated and a preliminary investigation made where this sub-system could be placed at the OSF. With the recent move of ALMA telescope control from the OSF to the Santiago Office, the room space that has become available in the OSF Control Room is considered a very suitable option.
- System sensitivity / performance allocation
    - To support system performance analysis and control in a systematic manner, it is strongly recommended to track performance and allocations to relevant sub-systems through system budgets. A simple spreadsheet based system budget for continuum system sensitivity is provided as an example.
- Delay tracking, fringe stopping, Walsh phase switching and LO offsetting
    - Considering expected changes to the signal path under the ALMA 2030 Architecture, e.g. no second heterodyne stage and revised correlator design, the implementation of delay tracking, fringe stopping, Walsh phase switching and LO offsetting have been reassessed versus the current architecture. Based on this assessment the SCWG concludes:

- DGCK-based fine delay correction, including with a correction per signal path, does appear feasible for ALMA 2030. We note however that lab demonstration of this in the near future is desirable, to ascertain the performance really offered by commercial PLL/VCO ICs with suitable programmable phase control. This could be part of the prototyping activity proposed in section 3.1.1;
- Three configuration options remain viable for fine delay tracking (hardware DGCK clock modulation, post-FFT phase slope correction, and fractional delay filters after an oversampling filter bank) and should be assessed on the merits of each design proposal in terms of performance, complexity, and cost;
- it is not recommended to modify the current 90° Walsh sequence implementation.

5.1.7 Charge 7 – Interfaces

The SCWG has assessed current interfaces between sub-systems covered by our charter and analysed these for the upgraded ALMA 2030 system architecture. In this context the relevant interfaces are:

- Interface requirements between Front End and Back End sub-systems:
- Interface between Front End / IF and Back End / IF Downconverter;
    - Interface between Front End First / Local Oscillator and Back End / LO References.
- Interface requirements between Back End and Correlator sub-systems.
- Interface requirements between Back End and Software sub-systems.
- Interface requirements between Back End sub-system and Site.
- Interface requirements between Back End and Antenna sub-systems.

Several devices in the current ALMA system will become obsolete in the ALMA 2030 architecture and will not have replacements:

- IF Processor Sub-subsystem (IFPS);
- LO2 related assemblies;
- Separate DTS receiver (DTSR) for a second (ACA) correlator.

5.1.8 Charge 8 – Frequency and Timing Distribution

Changes to the current ALMA Frequency and Timing distribution are expected to be limited to matters related to:

- Extended baselines
    - Future baselines, with antennas at a distance up to 45 km from the AOS Building, will require upgrades to several components of the Frequency and Timing Distribution, if line length correction is needed. Key aspects to be addressed are :

        - The Master Laser Coherence Length, to overcome the degradation of phase information (coherence) past the 50 % point as it has to travel to the antenna and back;
        - The real time Line Length Correction system, which needs to see both its range increased to accommodate the additional fiber span, and an increase in bandwidth to compensate for the increase time of flight of the Master Laser signal over the increased span;
        - An increase in fringe counter resolution and data throughput might be required, to offer the possibility of an asynchronous correction of the phase delay at the Correlator.
    - It should be determined if line length correction in such extended configurations is needed, or if astronomical phase referencing would provide sufficient correction alone. The development study that would test this has been on hold due to the pandemic and unable to test this aspect.

- Timing Event TE
    - Due to the need for time-stamping of digitized data at the antennas, a sufficiently accurate time reference is required. The performance of the current 48 ms TE signal shall be upgraded by using the low jitter 125 MHz reference frequency.
    - For M&C synchronisation it is recommended to use a network time protocol (NTP or PTP) in place of a hardware clock, as the precision is adequate, and it simplifies electrical connectivity. Suitable monitoring and alarms for time synchronisation status of devices should be implemented.

5.1.9 Miscellaneous Topics

Beyond the specific charges we have addressed, last, but certainly not least, the SCWG identified several issues that need further consideration and follow-up. We take the opportunity of this report to highlight some of these issues at an earlier stage since we are of the opinion that they can have profound impact on the ALMA 2030 upgrade, not only in terms of performance but also for costs and operational efficiency. In summary the major issues that we identified are:

- Radio Frequency Interference
    - Both internal as well as, future, external interference
- Reliability of AOS to OSF link to environmental factors
- LO1 tunability for Band-to-Band phase transfer
- Cosmic radiation impact on microelectronics
- Product lifecycle / lifetime
- Orphaned Products
    - Identify all necessary products and activities required for the ALMA 2030 upgrade project systematically with the support of product and work breakdown structures
- Requirements recommended by the various working groups shall be reviewed, formalized and issued in updated specification documents. The review of these recommended requirements should be done from a holistic system point of view against the ALMA 2030 science objectives.

5.2 Prototyping and Deployment

Aiming for a smooth transition from the current ALMA system to the ALMA 2030 system, with minimal operational down-time, requires careful scheduling of the roll-out of the various upgraded sub-systems. To reduce the risks in this roll-out a solid, well controlled design strategy supported by focussed prototyping activities are essential elements in this respect.

5.2.1 Deployment

Our top-level analysis has shown that only a parallel roll-out of ALMA 2030 system, while normal observations continue, can lead to a transition which meets the expectations of the scientific user community. In principle this parallel deployment could result to nearly zero observatory down-time with only slightly reduced performance, due to upgrading of antenna based electronics, over a period of about 1.5 years. Necessary conditions and constraints to realize this scenario are:

- 2nd Gen Correlator located in a new room at the OSF;
- Use of 2nd gas turbine to provide the increased electrical power draw during the transition phase;
- Use of new IF switches in each FE-assembly that allow routing the IF signals into the current Analog Backend or the new ALMA 2030 backend.

An often underestimated task, in fact a major project on its own, that needs further attention is the software required to match the upgraded hardware sub-systems.

5.2.2 Recommended Prototyping

Our general objective for prototyping is mainly to de-risk technological uncertainties for a new product under development. A prototyping activity can only be justified, since it is a very resource intensive activity, if it retires a major technical risk. Where feasible other options, e.g. modelling and simulation, should be considered as a, resource efficient, alternative.
With this strategy in mind, we propose the following prototyping activities to be considered:

- Asynchronous DTS
- Integration and Interface Verification
- Front End receiver Cartridges

5.2.3 NA 2nd Generation Correlator

From internal discussions as well as substantial interaction with a) the NA 2nd Gen Correlator proposal team and b) the group having done conceptual design studies on digitizers, DTS, and supporting DSP technologies it has become clear that this needs further attention and efforts beyond the SCWG charter. Integrating the 2nd Generation Correlator design and construction as proposed by the NA ALMA Executive in the ALMA 2030 upgrade and system architecture is a complex matter and sufficient time and effort should be dedicated to make well founded decisions by the ALMA Partnership. As much as feasible within the given time and information available to the SCWG we have made a preliminary impact analysis of the 2nd Generation Correlator design.

However final decisions on the ALMA 2030 system, including this NA 2nd Generation Correlator, can sensibly only be made by taking into account programmatic aspects, with an emphasis on, total, upgrade costs vs. science performance.

Last, but certainly not least, it is urged that the requirements recommended by the various working groups are reviewed, formalized and issued in updated specification documents. The review of these recommended requirements should be done from a holistic system point of view against the ALMA 2030 science objectives. Only a proper top-down strategy following established ALMA PA processes will lead to a satisfactory outcome.

6 Appendix A: Summaries of System requirements and relevant interfaces

6.1 BE-IF requirements

Requirements Level [RD25]: 0

Parameters	*Req. # [RD28]*	*Current Value*	*Proposed Value (minimum)*	*Proposed Value (stretched goal)*	*Comment(s)*
Analog power detectors: accuracy	511	Analog power detectors, baseband channel (2 GHz): Accuracy 1% of full scale (after linearity correction)	Analog power detectors, passband TBD. Accuracy 1% of full scale (after linearity correction)		Response of bandpass filter preceding detector to be defined
Analog power detectors: sampling interval	512	0.5 msec at >99 % efficiency	0.5 msec at >99 % efficiency		No change
Analog power detectors: 8 GHz	513	Not used for astronomy; for engineering monitoring only. Requirements are in BE sub-system requirements	Used for single dish solar observations, and for engineering monitoring. Accuracy TBD% of full scale (after linearity correction)		Although the current requirement doesn't foresee use of this power detector for astronomy it is actually used for solar observations. Accuracy to be defined. Might need detector zeroing capability to achieve accuracy.
LO Offsetting	446	Offset LO1, LO2 or TFB LO from their nominal	Offset LO1 or TFB LO from their nominal		See 2.7.4.4

		values by integer increments of 125MHz/2^{12} (30.5176 KHz)	values by integer increments of 125MHz/2^{12} (30.5176 KHz)

6.2 BE-Frequency/timing distribution requirements

Requirements Level [RD25]: 1

Parameters	*Req. # [RD26]*	*Current Value*	*Proposed Value (minimum)*	*Proposed Value (stretched goal)*	*Comment(s)*
Timing Event jitter	BEND-09500-00/RT	-	< 25 ps	-	Additional requirement. Physical transmission medium to be defined
Sampling clock fine delay	BEND-03230-00/RT (Req. #323 of [RD28])	Variable phase for fine delay with 1/16 sample intervals (15.625 psec) and accuracy.	TBD	-	See 2.7.4

6.3 DTS requirements

Requirements Level [RD25]: 0

Parameters	*Req. # [RD28]*	*Current Value*	*Proposed Value (minimum)*	*Proposed Value (stretched goal)*	*Comment(s)*
Digital Signal Transmission	311	The cable delay in each DTS should remain constant within +-8ns for at least 2 weeks.	The cable delay in each DTS should remain constant within +-8ns for at least 2 weeks.		No change for antenna pad to AOS cable. Will impact AOS to OSF span, see section 7.8
Digital Signal Transmission - Bit Error Rate	312	The Bit Error Rate (BER) for each DTS should be better than 10^{-6}.	The Bit Error Rate (BER) for each DTS should be better than 10^{-6}.		No change (See ALMA memo #349)
Digitization: channel bandwidth	321	2 GHz nominal channel bandwidth	16 GHz nominal channel bandwidth	20 GHz nominal channel bandwidth	See 2.3
Digitization: levels per sample	322	8 levels (3 bits), uniformly spaced, at 4 GSa/sec	64 levels (6 bits), uniformly spaced, at 32 GSa/sec	256 levels (8 bits), uniformly spaced, at 40 GSa/sec	See 2.3
Transmission span		< 15 km	< 75 km		See 2.3
Data transfer speed		120 Gb/s	1,200 Gb/s	1,600 Gb/s	See 2.3
Data protocol		Customized	Ethernet		See 2.5
DWDM based technology		Yes	Yes		See 2.3
EDFA required		Yes	Yes		See 2.3
RFI shielded		Yes	Yes		
Time-stamped data		-	Data shall have a unique time stamp		New requirement due to asynchronous DTS

6.4 ALMA Control Software requirements

Requirements Level [RD25]: 0

Parameters	*Req. # [RD28]*	*Current Value*	*Proposed Value (minimum)*	*Proposed Value (stretched goal)*	*Comment(s)*

6.5 Interface requirements between FE and BE

Requirements Level [RD25]: 0

Parameters	*Req. # [RD28]*	*Current Value*	*Proposed Value (minimum)*	*Proposed Value (stretched goal)*	*Comment(s)*

6.6 Interface requirements between BE and Correlator

Requirements Level [RD25]: 0

Parameters	*Req. # [RD28]*	*Current Value*	*Proposed Value (minimum)*	*Proposed Value (stretched goal)*	*Comment(s)*
Sampling clock synchronization to correlator	325	The synchronization between the DGCK sampling clock fine delay adjustment, that requires a transition from 15/16 of the period back to zero or vice versa, and the corresponding coarse timing adjustment in the correlator, that changes by 1 unit the coarse delay, shall be better than +- 500us.	TBD		See 2.7.4
Phase Switching Synchronization	444	Phase Switching synchronization between FLOOG (that applies the switch) and DTX (that removes it) in the same antenna shall be better than 100 ns Switching delay difference, among the 4 DTXs in each antenna	TBD		See 2.7.4

		shall be better than 100 ns After the delay correction applied in the Correlator, for antennas receiving the incoming signal in different times, the synchronization shall be better than 100 ns. Sign reversal relative to correlator dump, < 10 us	
Reference signals		125 MHz phase stable signal, 48 ms TE (Timing Event), 1 PPS (Pulse per Second) from MFS (Master Frequency Standard)	TBD

6.7 Interface requirements between BE and Software

Requirements Level [RD25]: 0

Parameters	*Req. # [RD28]*	*Current Value*	*Proposed Value (minimum)*	*Proposed Value (stretched goal)*	*Comment(s)*

6.8 Interface requirements between BE and Site

Requirements Level [RD25]: 0

Parameters	*Req. # [RD28]*	*Current Value*	*Proposed Value (minimum)*	*Proposed Value (stretched goal)*	*Comment(s)*
Max fiber optic cable length (CLO)	492	The fiber optic cable (LO, DTS & M/C) length from the AOS Technical Building to an antenna station shall be < 15 km	*30 km*	*45 km*	See 2.4.1 This change will affect Req #460 of [RD28]. “Allocation of Temporal Delay/Phase Stability Requirements” (Table 1 of [RD28] will be updated accordingly.

6.9 Interface requirements between BE and Antenna

Requirements Level [RD25]: 0

Parameters	*Req. # [RD28]*	*Current Value*	*Proposed Value (minimum)*	*Proposed Value (stretched goal)*	*Comment(s)*

7 Appendix C: Contribution related to SCGW Charge 1 from ACS Lead

Upgrading the ALMA Monitor & Control Bus

Ralph

Marson

2021-06-10

Before ALMA construction formally started, in 2002, it was decided that the Controller Area Network (CAN) would be used by the software for the monitor and control of ALMA electronics. CAN had a number of attractions.

- It is a simple packet-based message format with a header, address and checksum. This allowed multiple devices to share the same CAN bus.
- The bus is a simple twisted pair that can connect dozens of devices in a daisy chain. CAN was designed for automotive applications to perform better in noisy electrical environments.
- A protocol, the ALMA Monitor and Control Bus (AMB), could readily be designed to ensure the bus was deterministic. This protocol avoided packet collisions that would invoke the arbitration mechanisms in CAN. These arbitration mechanisms would delay CAN communications.

During ALMA construction a number of CAN interface cards were used. Two versions of the ALMA Monitor and Control Bus Standard Interface (AMBSI) cards were developed in house.

1. The AMBSI-1 was a postcard sized PCB that contained a CAN controller chip and a programmable microcontroller to 1) manage CAN communications and 2) use a range of digital and analog inputs and outputs supported by the microcontroller. Software was written for this microcontroller that implemented the AMB protocol and could readily be expanded to use any of the I/O ports on the microcontroller. The AMBSI-1 is used in all front-ends (FEMC).
2. The AMBSI-2 is a large-stamp sized PCB that contains a CAN controller chip and an FPGA. It's just a CAN to SPI translator and is not customizable. The FPGA implements the AMB protocol, manages the CAN controller and the data flow between the SPI and CAN buses. The AMBSI-2 was more widely adopted and is used in the majority of the ALMA back-end equipment.

Neither of these AMBSI cards was used in some ALMA equipment. Notable exceptions include:

- The bus master computers. The AMB protocol specifies that one device, the bus master, manages all CAN communications on each CAN bus. The bus master is a general-purpose computer with a commercial CAN interface card, the TEWS TPMC-901 CAN interface card. Bus master computers include the Antenna Bus master (ABM) & Correlator Control Computer (CCC).
- The Antenna Control Units (ACUs) in all antenna types. The ACUs are also general-purpose computers and use a commercial CAN interface card. The TEWS TPMC-901 is widely used by

the ACUs.

- The baseline correlator. Various parts in the correlator, like the Station Control Cards (SCC) or Long-Term Accumulator (LTA) use the same CAN controller chips and microcontrollers as in the AMBSI-1 card but in a custom PCB.

CAN has worked well for ALMA. After commissioning issues were fixed there have been no long-term systematic issues with CAN communications.

However, the limitations with CAN are making upgrades difficult. The most important of these are:

- Limited bus bandwidth.
  The CAN bus has a maximum data rate of 1Mbit/sec. This is enough for routine monitor and control applications where commands are sent no more frequently that once every 48ms or monitor points are sampled every 5 seconds. But it limits high-rate monitoring when diagnosing problems. It’s too slow to convey the IF power, sampled every 0.5ms, by the IF processors; where an Ethernet connection is used. Changes that want to significantly increase the monitoring rate or the rate which commands are sent cannot be accommodated.
- Limited bus length
  At a data rate of 1Mbit/sec the CAN bus cannot be more than 40m in length.
  This requires a bus master computer be located near the associated hardware. For example, an ABM is located in the receiver cabin of each antenna. Because of the accelerations it’s a more expensive specialized computer that has, for example, all the memory chips attached to the mother board.
  The length limitation means it is not possible to have one bus that snakes it way thought each antenna or throughout the baseline correlator. Instead, multiple buses are used and his explains the popularity of the TEWS TPMC-901 CAN controller card that supports 6 CAN buses.
- Limited software support
  Software updates are rarely done for the microcontrollers in the correlator or the AMBSI-1 card. That’s not true for the bus master computers that run the Linux operating system. To maintain uniformity with other ALMA computers their operating system gets updated every few years.
  This requires an update of the CAN controller driver software that is not included in the operating system. ALMA maintains the CAN driver software. The interval between operating system updates is long enough that each update requires relearning how to port and maintain Linux kernel modules. Debugging problems in this area is difficult.
- Reducing industry support
  CAN-2.0, the standard used by ALMA, is deprecated. CAN-2.0 controller cards, of the sort needed by the ACUs and bus master computers are difficult to find. The TEWS TPMC-901 is no longer sold. The automotive industry is moving to a new standard CAN-FD.

In the last two decades CAN has seen some development. CAN-FD increases the maximum data rate to 5Mbit/sec and the maximum data payload to 64 bytes. CAN XL plans to increase the maximum payload to 2048 bytes. CAN has not expanded its user base beyond the automotive industry.

The standout comparison is with Ethernet which has been around for longer than CAN, been adopted in many areas and undergone orders of magnitude improvement. Right now, Ethernet data rates are over 1000 times faster than CAN and Ethernet packets can support data payloads of 9000 bytes. For monitor and control ALMA does not need this much improvement. What it needs is a technology that will continue to exist decades from now. Because of its widespread adoption Ethernet is far more likely to continue to exist. Its widespread adoption also means that other equipment, from computer cards, software drivers, and network switches will be more available without the need for custom solutions that are maintained by ALMA.

Ethernet was around when ALMA decided to use CAN. It was not selected because determinism of the monitor and control bus was believed to be of critical importance. It ended up being unimportant because ALMA does not have high bandwidth loops that need to be closed through communications with the monitor and control computers. The high bandwidth of modern Ethernet systems means that packet collisions will be of minimal consequence to communications. And improvements in technology mean embedding Ethernet interfaces and associated processors in new ALMA equipment is now far simpler than it was 20 years ago. Because Ethernet packets are repeated through switches the general- purpose computer that sends monitor and control signals does not need to be near the associated hardware. These computers could be moved to the OSF where they are easier to maintained and specialized computers are not needed. Instead cheaper more readily replaceable computers can be used.

Replacing CAN with Ethernet will put more demands on the hardware. Equipment like the ACU, FLOOG or parts of the correlator, that need to do things at specific timing events will need to “know” the time of each timing event and be able to queue time-tagged commands and monitor requests sent a few second earlier. This requires a way to establish the time on all this equipment. This is already done when all bus master computers synchronize their time with the bus master (ARTM) connected to the GPS and Central Reference Distributer (CRD). With an Ethernet interface this synchronization gets moved to the hardware; or the precision time protocol could be used.

A disadvantage of switched Ethernet is that it uses a star topology instead of the daisy chain used by CAN. This increases the amount of wiring as there is a separate cable from each device to a centrally located switch rather than a single daisy chained cable that snakes around the antenna or correlator room.

I (Ralph) believe the SCWG committee should recommend:

1. New ALMA equipment should not use CAN. ALMA should investigate and adopt a new preferred monitor and control bus and Ethernet is the front-runner amongst the alternatives.
2. ALMA staff should then investigate and recommend the protocol to replace the AMB. This protocol should be focused on monitor and control and, if possible, be a standard that is likely to persist for at least two decades. Possibilities include UDP, TCP or a higher-level protocol like OPC.

An additional requirement that I think should be added for all new equipment, that is peripherally related to the monitor and control bus, is

3. The firmware/software of all equipment should be updateable through the network from the OSF.