Central
Development
Laboratory

NA ALMA Development Cycle 7 Study
ALMA Central LO Improvements and Upgrades

Final Report

27 November 2023

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ALMA Central LO Improvements and Upgrades

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NRAO
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1. Executive Summary

This is the final report for the ALMA Cycle-7 Development Study 654, titled, “ALMA Central LO Improvements and Upgrades”. It presents the results obtained to evaluate the impact of ALMA 2030 goals on the baseline Central LO Article (CLOA) hardware and layout, and identifies avenues for upgrades and/or new development. This study focused on four main ALMA2030 goals which directly impact the Central LO. It was determined that meeting the requirements derived by two of the four (CLOA2030-2: Increasing the total number of antennas, and CLOA2030-3: Increasing the dynamic range and resolution of the active phase correction) are straightforward and should not require a major investment of resources or funding to upgrade the central LO system. For the other two (CLOA2030-1: Extending ALMA baselines by up to 45 km and CLOA2030-4: Increase Array visibility and coherence), the existing hardware can only be modified to yield limited immediate improvements: a 5 km increase in the AOS to antenna pad distance, and an increase in Band 1 frequency range. To achieve all of the required technical goals (especially the 2x and 3x baselines), a significant R&D investment will be necessary to produce a new Master Laser with the required (very high) coherence length. This study was conducted during the challenging COVID timeframe (2020-2021), so no in-person visits or conference attendance were possible.

2. Acronyms

ATAC:	**A**dvanced **T**echnology **A**lma **C**orrelator (aka “the second-generation correlator”)
AOS:	**A**rray **O**perations **S**upport center, located at 5,000 m
CLOA:	**C**entral **LO** **A**rticle
EDFA:	**E**rbium **D**oped **F**iber **A**mplifier
LLC:	**L**ine **L**ength **C**orrection
LO:	**L**ocal **O**scillator
LRU:	**L**ine **R**eplaceable **U**nit
LS:	**L**aser **S**ynthesizer
OSF:	**O**perations **S**upport **F**acility, located at 3,000 m
MFS:	**M**aster **F**requency **S**tandard
ML:	**M**aster **L**aser
Rb:	**R**ubidium (gas cell)
TE:	**T**iming **E**vent, the 48 ms pulse used for timing
WCA:	**W**arm **C**artridge **A**ssembly

3. Baseline Specification and Upgrade Goals

The baseline ALMA Central LO (CLOA), as installed and commissioned, provides each of the 66 ALMA antennas, regardless of type, with a set of highly coherent and stable LO signals composed of two phase-locked laser tones and one modulated one, with the following specifications (*guaranteed vs. temperature, time, 15 km fiber length, antenna motion, …)*:

- A near continuously tunable (27 ~ 33 GHz, 67 ~ 121.7 GHz), fast switching reference, and the 20.833 Hz (48 ms) TE, 25 MHz, 125 MHz, and 2 GHz references needed by the Front End (FE)-receiver systems at the antennas.

- Four (4) independently tunable subarrays, expandable to six (6).
- 1st LO rms integrated phase noise < 53 fsec at the highest frequency.
- 1st LO residual phase drift < 18 fsec (3.6 microns) over an AOS-to-antenna pad distance of 15 km, with active stabilization.
- 1 hour reset-free operation & 24-hour polarization calibration stability.

These specifications required the use of very low-noise oscillators, in a stable thermal environment, and the use of active phase (path-length) correction to cope with antenna motion, temperature fluctuations, and fiber polarization effects.

From the ALMA ASAC 2030 Roadmap document, the following subset of technical goals were identified for this study:

CLOA2030-1: Extending ALMA baselines by up to 45 km (3x current)
CLOA2030-2: Increasing the total number of antennas
CLOA2030-3: Increasing the dynamic range and resolution of the active phase correction
CLOA2030-4: Increase Array visibility and coherence

The above requirements are interconnected, and meeting each of these goals has an impact on the others. The baseline CLOA is a holistic design where each subsystem is dependent on the ones upstream and downstream.

Most measurements presented in this report were performed using a laboratory two-antenna end-to-end ALMA system (starting at the Rb MFS and up to and including the Band 6 WCAs) made up almost entirely of full production grade LRUs and components, housed in an enclosed space with raised floor ventilation, to closely replicate the AOS CLOA room. This system is referred to in this document as “cvCLOTS” (**C**harlottes**v**ille based **C**entral **LO** **T**est **S**tand).

4. Extending ALMA Baselines (CLOA2030-1)

4.1 Overview

One of the important goals of the ALMA2030 vision is to extend the baselines to increase imaging resolution. However, as explained in Section 2, the Central LO is a high-performance system designed to work at very high frequencies, but only to an AOS-to-antenna-pad distance of up to 15 km. Extending the antenna baselines (the maximum distance between antennas) first to 30 km then to 45 km will require the LO signal to and from the CLOA to be stronger than it is now, with a laser coherence length of at least double the antenna-pad distance, for the round trip phase correction system to work.

4.2 Twenty-kilometer AOS-to-pad spans

The optical amplifiers used in the CLOA determine the power reaching the antennas, which implies that increasing their output power should allow a corresponding increase in distance. In the case of the CLOA, a few dB increase would be required to achieve the 20 km spans, up from the current 15 km. However, component ageing has resulted in the need to increase the output of the amplifiers to compensate, and some amplifiers have now reached the safety limits which prevent them from producing higher output powers. The Master Laser Distribution (MLD-PM) is operating at or close to its maximum permissible output power level, its gain having been adjusted to reduce the number of locking failures of the ageing Laser Synthesizers. The return signal also needs to be amplified to reach the LLC detection circuit (VDET) and lock it with sufficient power.

Consequently, if we were to only increase the pad distances by 5 km or less, we would need to procure higher output power MLD-PM and Photonic Reference Distribution (PRD) EDFAs, that can produce about 3 dB more per output port (i.e. per antenna). This was tested using cvCLOTS, and we demonstrated that the CLOA can achieve a reliable lock at up to 20 km of distance (at Band 6). The modest increase will not impact laser safety: IEC Class 3b eye-safe laser devices must remain below the 27 dBm (500 mW) limit. All CLOA EDFA units are rated as Class 3b devices and have the corresponding safety measures in place.

Upgrade CLOA2030-1-A: Procure higher output power +16 dBm per port MLD-PM and increase the current PRD output to +22 dBm per port, to readily achieve 20 km baselines.

Note: a careful choice of the new pad locations can yield an increase in baselines while remaining within the 20 km antenna pad-to-AOS distance. See below.

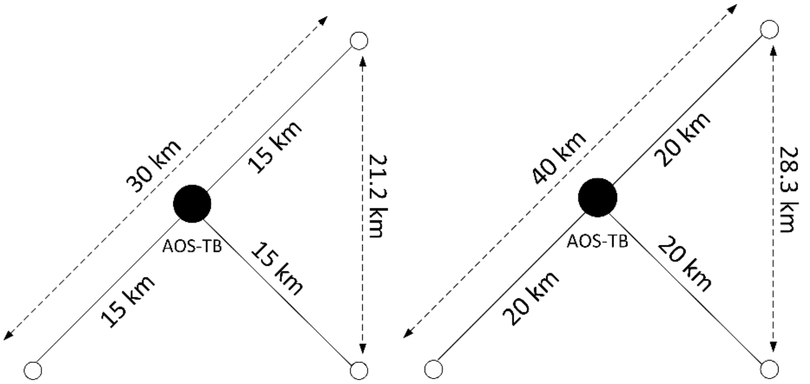


Fig 1: Baseline increases a) within current 15 km (left), b) within a 20 km CLOA limit (right)

4.3 2x and 3x baselines

4.3.1 Bidirectional EDFA

To further increase the baselines, assuming a Reference Laser with enough coherence (see 3.3.2 below), a simple solution consists in placing a custom bi-directional optical amplifier (b-EDFA) in the LO path, to increase both the light reaching the WCA photomixers and the return signal to the LLC. Since most commercially available bi-directional EDFAs are in fact two amplifiers fed at each end by optical circulators, the split path design results in substantial differential phase drift, due to the polarization effects of the circulators (a state of polarization change results in phase variations). Because the complexity and required gain levels are not important, it is possible to design and construct a bi-directional unit that is below the oscillation (lasing) threshold:

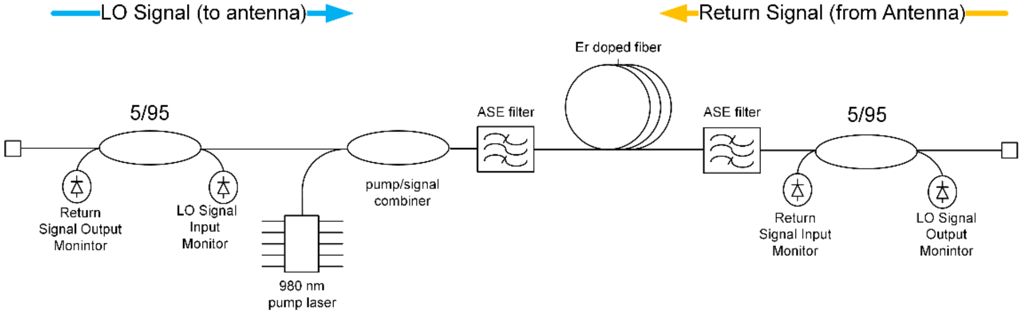


Fig 2: layout of a bi-directional EDFA for use with the farthest pads

Such an amplifier was designed, built, and tested using cvCLOTS. The typical output is shown below, with the 1530 gain peak suppressed by the ASE filters to prevent "lasing". A typical Erbium doped fiber emission cross section graph (in green) is shown below. The curve directly correlates to the gain of the amplifier, illustrating why the peak must be attenuated:

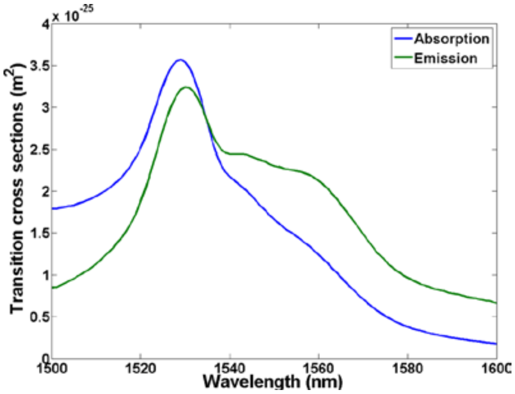


Fig 3: Absorption and Emission cross sections of Erbium

The output spectrum of the EDFA is shown below.

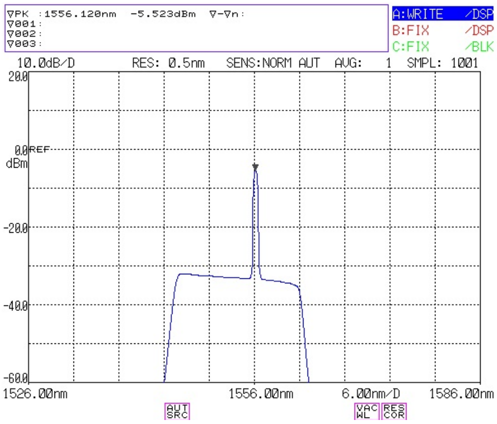

```
∇PK  :1556.120nm  -5.523dBm  ∇-∇n:
∇001:
∇002:
∇003:
```
```
10.0dB/D        RES: 0.5nm   SENS:NORM AUT   AVG:    1   SMPL: 1001
```

Fig 4: output of "LO signal" portion of bi-directional amplifier

Note that this amplifier cannot accommodate the 1532 nm low frequency references (LFR), so a more complex design is required, but the prototype provides the basic proof of concept.

Using an optical attenuator to simulate the attenuation due to distance (without the corresponding degradation of ML coherence), we were able to demonstrate that the modest gain provided by the prototype EDFA allowed the CLOA system to lock reliably with enough return power for up to 70 km of simulated distance (at Band-6).

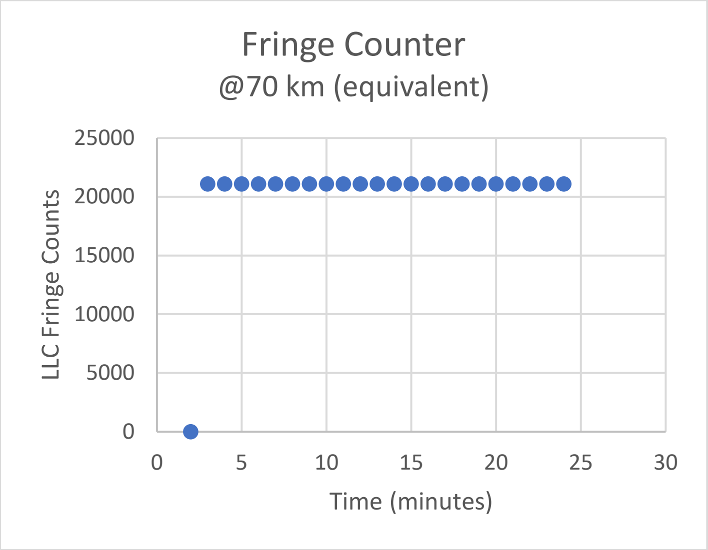


Fig 5: LLC fringe counter. X-axis is time, Y-axis shows fringe counts (first point was taken before locking).

Upgrade CLOA2030-1-B: When designing the new cable route for the extended baseline antenna pads, incorporate a mid-span equipment hut to house bidirectional EDFAs, complete with power and M&C communications.

4.3.2 New Reference Laser (ML)

The ALMA CLOA accomplishes long term phase stability by correcting the round-trip phase of a high-coherence (narrow-linewidth) and wavelength stabilized master laser. The master laser has a dual function in the central LO. The first specialized function is that it serves as the wavelength reference for the LLC round-trip phase correction. The second function is that it serves as one of two lasers that together form a dual-laser heterodyne such that the difference frequency between the two lasers represents – and is converted into – the ALMA LO reference frequency, which in turn governs the frequency and stability of the ALMA first LO at the individual antennas. Most of the engineering requirements that make the master laser a bespoke and specialized design are necessitated by the round-trip phase correction function. In particular, the high coherence is required so that the round-trip phase correction can be performed by use of the master laser in two arms of a Michelson interferometer. The round-trip phase correction interferometer consists of a short reference arm, and a long arm constituted by the optical fiber path from the ALMA central building to the antenna. The master laser coherence length must be equal to or greater than twice the longest central building to antenna fiber distance/span. The master laser wavelength stabilization is also needed for the round-trip phase stability, since the relative accuracy of the correction is proportional to the wavelength stability/accuracy of the laser. The ALMA phase stability allocation for the 1st LO reference is 13 fsec, equivalent to a free space path length of 3.9 microns – which is very small compared to the maximum fiber optic path length to an antenna (15 km). The relative stability of the antenna fiber path must thus be on the order of 10^{-6} meters/10^{4} meters or ~10^{-10}. Consequently, the master laser must have a wavelength (or, equivalently, frequency) stability on the order of 10^{-10}. Since the laser frequency is ~192 THz, the wavelength stability needs to be around 20 kHz (in practice it was engineered to be 10x better than that). Such high level of stability is not possible with a commercial laser, even with exceptional temperature control. Additional engineering measures are needed. For this reason, the ML includes a wavelength stabilization physics package containing a Rubidium gas cell used for the wavelength reference and stabilization servo.

The key specifications of the Reference Laser (apart from operational, packaging, and environmental characteristics) for the baseline 15 km array are:

1. Wavelength	1556.21 nm +/- 0.01 nm	This is the absolute wavelength requirement. Although a different ML could in principle operate at a different wavelength, any deviation from this would create a wavelength compatibility issue with other ALMA LRUs, such as the Laser synthesizer and the subarray switch fiber Bragg gratings. This change would thus entail undesirable downstream changes with cost and performance risks.
2. Wavelength Stability: Allan Standard Deviation	$\sigma(2, T=\tau, \tau = 10\text{ ms}) < 4.4\text{e-}11$ $\sigma(2, T=\tau, 10\text{ ms} < \tau \leq 100\text{ ms}) < 4.4\text{e-}11 * (10\text{ms}/\tau)^{0.5}$ $\sigma(2, T=\tau, 100\text{ ms} < \tau \leq 10\text{ s}) < 1.4\text{e-}11$ $\sigma(2, T=\tau, 10\text{ s} < \tau \leq 1000\text{ s}) < 4\text{e-}11$, goal of 1.4e-11	The Allan deviation is specified from 10 ms to 1000 s. It is based on a well-developed theory of how the wavelength stability would impact the overall performance of the ALMA round trip phase correction.
3. Coherence Length	80% for 30 km fiber using 1 ms measurement time (goal) 50% for 30 km, or 1 kHz linewidth over 120 ms, required	The coherence length is critical for the proper functioning of the round-trip phase correction.
4. Dithering and Modulation	Not to affect any other requirement	This requirement was included to make clear that any intentional dithering of the laser (which is common in stabilized lasers) shall not affect the satisfactory meeting of the stability and coherence requirements.

5. Relative-Intensity-Noise	< 1 MHz 1 MHz-2 MHz 2 MHz- 5 MHz 5 MHz-20 MHz 20 MHz – 12 GHz	<-90 dBc/Hz <-115 dBc/Hz, <-120 dBc/Hz < -130 dBc/Hz < -140 dBc/Hz	All lasers have relative intensity noise, which usually includes a peaking at some offset from the carrier. This requirement guarantees that any peaking does not interfere with the 1st LO phase noise performance.

The technical hurdle that this study was not able to identify a solution for was the 1556 nm Reference Laser Coherence Length, which is about 45 km for the Teraxion units currently installed and which allows the CLOA to function up to 20 km, as stated in section 3.2. To achieve a reliable lock at longer distances, the return signal must have more than 50% phase coherence at the LLC detection point (item #3 in the table above). This means a laser coherence length of approximately 60 km and 90 km for the 30 km and 45 km baselines respectively.

The primary hurdle was identification of a new laser head, one that offered better native linewidth (before incorporation of correction systems for coherence and stability). A search of potential replacements yielded very few candidates (only two), and follow-up discussions with these manufacturers revealed that none could realistically achieve all of the required specification parameters simultaneously. The conclusion was that, just as was originally the case with Teraxion, this would require extensive development work (and funding) to yield performance metrics that were similar to the current baseline Master Laser.

Furthermore, Teraxion, the current ML OEM, was contacted and requested to investigate whether the stated ALMA2030 goals could be met by a Reference Laser incorporating an improved linewidth reduction system. Originally, the ML prototype was slated to have one, but it was not deployed as the loop was shown to be unstable at times. This linewidth improvement scheme would be compatible with the current stability feedback system based on the Rb gas cell, as such a wavelength stabilization system is still considered the gold standard. The results from Teraxion were inconclusive, as a detailed study would have taken more time and funds than this project could accommodate, and its execution would have faced the COVID-related work constraints. So this line of investigation was not commissioned and remains in the “to be done” category.

5. Increasing the total number of antennas (CLOA2030-2)

Another ALMA2030 goal is to able to observe with seventy antennas, which in the short term means adding up to four antennas to the array. Indeed, the new Advanced Technology ALMA Correlator (ATAC) project, currently under way, will be able to handle the data from seventy ALMA receivers.

Since the original ALMA design called for a total of eighty antennas (sixty-four 12-meter baseline plus sixteen 7m/12m for the Compact Array), the CLOA group decided not to reduce the total number of outputs after the mid-2000s re-baselining, and thus, as delivered, the current CLOA can already accommodate a total of 80 baseline receiver Front Ends. All that is required is to populate the corresponding SAS (Sub Array Switch LRU) and LLC (Line Length Correction LRU) slots for each antenna added. Everything else is already in place, with no modifications or upgrades required. As the ATAC can handle seventy (70) antennas, four more than the current ALMA array, this would still leave ten (10) slots available for future upgrades (see section 5.2)

Upgrade CLOA2030-2: For each additional antenna, simply procure an SAS and LLC LRU pair in the corresponding (already existing) slots.

6. Increasing the dynamic range and resolution of the active phase correction (CLOA2030-3)

6.1 Overview

Increasing the Dynamic Range, Fringe Counter Resolution and Functionality of the Active Phase Correction (Line Length Corrector) is an essential part of extending the baselines, as the increased distance results in the need for an increase in the range of the active correction of the optical path. Additionally, there may be a future need for an accurate measurement of the phase changes to enable a software-only based correction implemented asynchronously in the Correlator, rather than in real time.

6.2 Stretcher Range Increase

The fiber-stretcher reacts to the net sum of fiber length change between the LLC and the LO Photonic Receiver, and consists of various sections of fiber cable in different environments. There is fiber in the AOS Technical Building, buried fiber, fiber in joints (manholes), in the antenna pedestal, a run up the antenna, in the receiver cabin and in the receiver itself up to the Faraday-mirror. These environments can all be assumed to have diurnal temperature changes, as well as cyclical changes on shorter time scales. The magnitudes of these changes are generally related to the overall length of the fiber being controlled. As the baselines are extended, the dynamic correction range of the Line Length Correction system (the "stretch range") may need to be increased from its current 4.5 mm nominal value. The original baseline design assumed 1.6 mK temperature change per hour for the buried cable and a temperature coefficient of approximately 6 ppm/K for silica based optical fiber. Using these values, it was estimated that an antenna located up to 30 km from the AOS would not need more than the 4.5 mm of stretch range that is available with the existing LLC. At up to 45 km, an increase (to 6.5 mm) is warranted to cover the full 300 and 1000 s observing intervals. This enhanced stretch range would also provide for a much longer reset-free operating time for antennas located at 30 km or less.

The original supplier of the custom fiber stretchers (General Photonics) was contacted and asked to review a new set of specifications, including increasing the correction loop bandwidth (goal: 200 Hz), and targeting a 50% increase in total stretch range (about 6.5 or 6.75 mm). They report that while an increase of bandwidth and range should be feasible, it would result in an increase of the physical width of the final assembly. A possible avenue would be to make the modules double the current footprint, so as to accommodate them within the current available subrack space and configuration. Currently, there are 14 slots free, consequently it should be possible to accommodate double-width modules, and thus a mix of extra antennas and/or antennas located at 45 km from the AOS-TB, with strict configuration control being necessary during operations. Prototyping would have required a substantial amount of NRE costs, and was not pursued for this study.

Upgrade CLOA2030-3-A: A 6.5 mm stretcher, for pads located at more than 30 km, is technically feasible and could be made to fit into the current LLC subracks using a double-wide module. The current stretcher would work for pads located up to 20 km from the AOS.

6.3 LLC Mainboard Upgrade

As the current Line Length Correction (LLC) modules age, serious consideration is being given to the development of a "software based" phase tracking and correction system, where the Correlator could apply a phase correction based on an accurate record of phase information (fringe counts) sent from the CLOA. This would also alleviate/eliminate the need for the increased range physical stretchers, as well as provide better resolution measurements for the fringe counter.

The fringe counter on the original LLC board was never intended to be used for phase correction in the correlator. It was only designed as a proof of concept device and a troubleshooting tool. To be useful for phase correction in the correlator, several improvements need to made to the existing fringe counter design. First, the production LLC fringe counter does not have sufficient phase resolution to meet the ALMA phase specifications. On the production LLC fringe counter, a 50 MHz signal is returned from the antenna, this signal is divided by 10 and compared against a 5 MHz reference. The divide by 10 operation filters out all of the phase information above 5 MHz. A second issue with the production LLC is the limited bandwidth of a relatively slow ALMA monitor bus (AMB). AMB is designed to interrogate modules at a maximum rate of once every 48 ms which may not be sufficient to meet the ALMA phase correction requirements. Additionally, the production LLC fringe counter occasionally returns incorrect, "glitchy" data. This is caused by flaws in the CPLD implementation of the fringe counter. The existing CPLD does not have sufficient resources to correct this by upgrading its firmware.

To resolve these issues, a new prototype LLC board was designed and built. The prototype LLC board (see figure below) used a single Zynq System-on-module (SoM) to replace the microcontroller and CPLD of the production LLC. The Zynq SoM has sufficient programmable logic hardware on board to correctly implement the high-resolution fringe counter. It also has a 1 Gb Ethernet interface for increased communication bandwidth. Use of a 50 MHz reference signal (instead of the 5 MHz signal) provides sufficient phase resolution to meet the ALMA phase specifications.

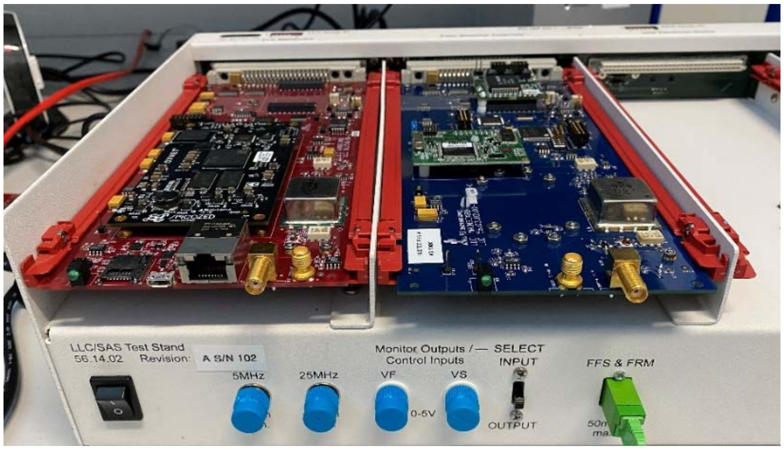


Fig 5: The new LLC Mainboard (left), and the existing baseline one (right).

This new LLC Mainboard is a drop-in replacement for the existing one. To test the new system, the production LLC test stand system was used. The return signal was split and fed into the photodetector circuit of both an old and new board. Software was written to record data from both LLC boards simultaneously and the results were plotted.

The logging data acquisition software was modified to achieve the maximum sampling rate with the available hardware. The Windows OS computer can sometimes limit the sampling speed to about 1 ms, which would not be the case in the Linux based CLOA. Even so, there was a 2.87x increase in bandwidth with the prototype LLC Zynq over the production LLC.

Hardware	Sampling Rate
Prototype LLC	2.2 kHz
Production LLC	0.75 kHz

A real-time operating system would increase the sampling rate for both systems. ALMA Line Length M&C Computers (LMCs), which are real-time machines, could likely be configured to read fringe data every 48 ms even with the production LLCs. However, it was observed that the Production LLC was not able to reliably read fringe counter data. Seventy-five minutes of fringe count data was acquired at maximum speed. Out of 3479858 total reads, the production LLC reported 42 impossible fringe count values which is one error out of every 83k reads. This would not be acceptable for software phase correction. By comparison, the prototype LLC did not report a single impossible fringe counter value during the test.

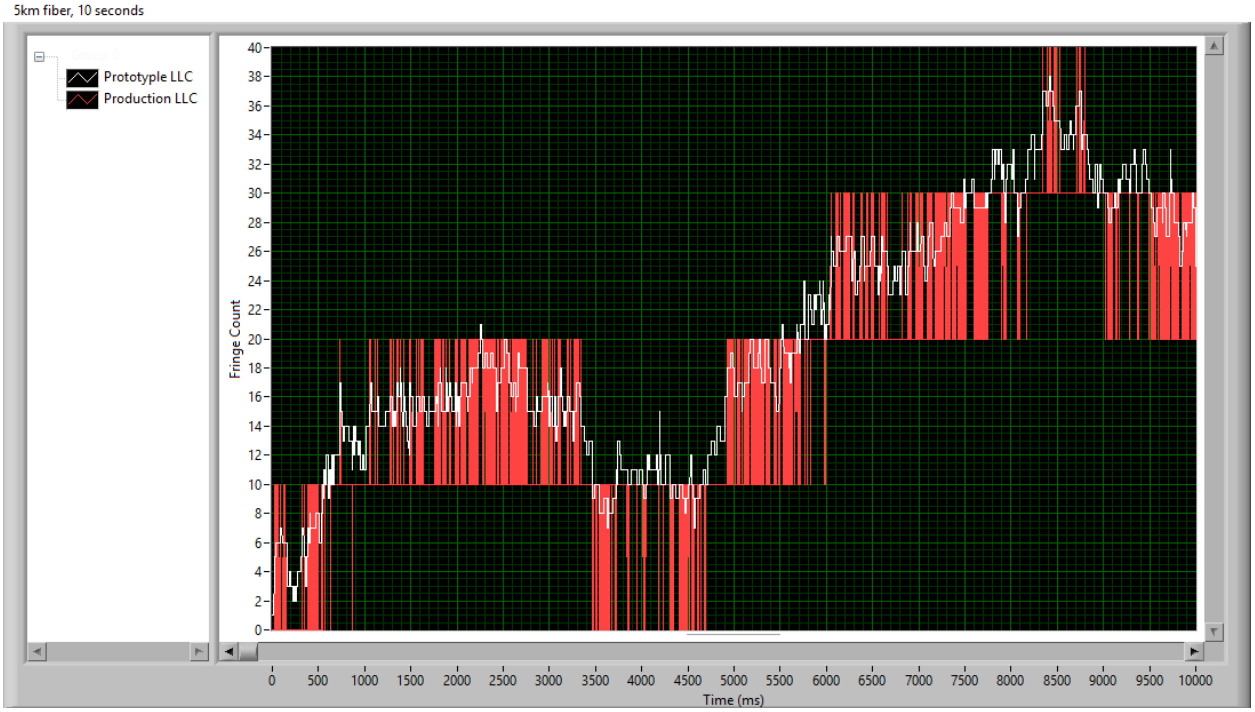


Fig 6: Phase drift tracking with the upgraded LLC Mainboard (white) vs Baseline system (red)

In conclusion, to minimize the risk of LLC failures due to age, both the ALMA correlator and software teams should start considering an asynchronous phase drift correction technique that no longer relies on mechanical stretching of the optical fiber. It has been demonstrated that this can be achieved with great precision at a rate of 20.8 Hz (corresponding to 48 ms). For the CLOA side of the software correction approach, the hardware upgrade cost is estimated at USD 2,000 per LLC. For longer baselines, this would alleviate the need for new, expensive stretchers with increased stretch range. The cost to ATAC and ALMA software was not analyzed as part of this study.

CLOA2030-3-B: To implement an asynchronous, software-only phase detection and correction, the the current 5 MHz LLC Mainboard in the CLOA should be upgraded to a new 50 MHz design.

7. Increase Array visibility, efficiency, and coherence (CLOA2030-4)

7.1 Overview

This section summarizes the work done to determine ways in which the photonic LO can be amended or improved to meet the science objectives. The scope was limited to primarily studying upgrades to the laser synthesizer and ways it could be improved (range, speed, phase noise):

- Improved interferometer coherence: the ALMA system phase stability requirements were set for the electronics and the antenna structure by requiring that their root-sum-square stabilities shall be better than the atmospheric stability (after water vapor radiometer corrections are applied) 95% of the time (see ALMA System Technical Requirements, ALMA-80.04.00.00-005-B-SPE). Furthermore, the electronics was allocated 75% of the stability budget while the antenna was allocated the remaining 25% of the budget. At 53 fs, the first local oscillator was allocated the largest portion of this budget. This implies a coherence loss of 10% in Band 10 (i.e $e^{-\omega^2\tau^2}$). By improving the laser synthesizer, it should be possible to recover most of this LO coherence loss. This would be a direct improvement to the ALMA observing efficiency and is in particular applicable to the highest bands and the best (stable) observing time periods.
- Improved Observing efficiency: A reduction in the locking time of the laser synthesizer will reduce overhead and increase telescope efficiency. This will impact science programs which require frequent and multiple LO retuning.

7.2 Increasing 1st LO tuning range for Band 1

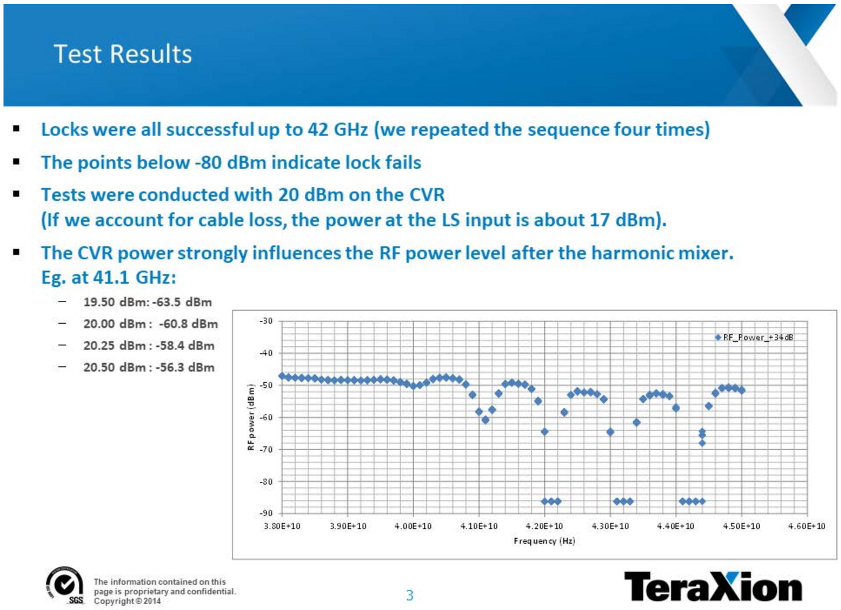
As they were delivered over a decade ago, the baseline laser lynthesizers meet the specification of a 27 to 33 GHz tuning range for Band 1 [ALMA-40.10.00.00-50.03.00.00-A-ICD]. As installed, the original built-in tuning margin, along with an M&C software upgrade, now permits the laser synthesizer to tune to just above 38.5 GHz, as demonstrated by measurements carried out on all five (5) production units, see BEND-56.11.00.00-0038-A-TDR (Sept 2021).

The newest Band 1 requirement goal, which requests a ≥ 40 GHz 1st LO reference, to be able to achieve a 52 GHz sky frequency observation, is simply not possible with the current hardware. The following relation shows the relationship between LO and CVR:

$$f_{LO}(max) = (2 \times f_{CVR}) - 125\ MHz$$

and yields a 39.875 GHz theoretical upper limit as the CVRs have a hardware limit of 20.00 GHz. Adding the needed 1.5 GHz to the LO tuning range would seem to require an extensive redesign of the LS locking hardware. Another avenue was thus explored.

A simpler solution for the two upgrades was identified and attempted by the group: a higher frequency CVR LRU (able to tune above 20 GHz) and a firmware upgrade to change the limits of the Laser Synthesizer locking algorithm. Working with the original LS manufacturer (Teraxion), the cv-CLOTS spare unit was upgraded, and a 40 GHz Signal Generator (meeting all ALMA requirements) was purchased for in-house use with cv-CLOTS. The initial results below show that the upgraded CVR + LS can provide a phase-locked LO past 41 GHz:



Test Results

- **Locks were all successful up to 42 GHz (we repeated the sequence four times)**
- **The points below -80 dBm indicate lock fails**
- **Tests were conducted with 20 dBm on the CVR**
  (If we account for cable loss, the power at the LS input is about 17 dBm).
- **The CVR power strongly influences the RF power level after the harmonic mixer.**
  Eg. at 41.1 GHz:
  - 19.50 dBm: -63.5 dBm
  - 20.00 dBm : -60.8 dBm
  - 20.25 dBm : -58.4 dBm
  - 20.50 dBm : -56.3 dBm

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TeraXion

Fig 7: Locking test results of a production LS past 38 GHz, after the extended tuning range firmware upgrade.

This upgrade is fairly straightforward, and has been performed on Laser Synthesizer 105, currently installed in cv-CLOTS. Installing this unit in the CLOA, along with a new Keysight 31.5 GHz low phase noise, high power CVR unit (this is the lowest cost unit that will meet all the requirements, and is fully compatible with ALMA systems, at time of writing) would quickly enable Band 1 observations up to 53 GHz (official goal is 52 GHz) on the sky.

The initial upgrade estimate is USD 85,000.00 for the first unit (new CVR + firmware upgrade of the Laser Synthesizer + Acceptance testing/PAI in CV, labor and travel time for PAS, PMD, …), and USD 315,000.00 to upgrade the remaining 4 subarrays, for a total of USD 400,000 to upgrade all 5 subarrays in order to meet Band 1 goal range.

However, issues like Phase Noise and fast switching (especially between 39.1 and 40.1 GHz, where the CVR switches internally) were not extensively tested. Phase noise values for the LO between 33.0 and 41.0 GHz, which were not part of the original specification, remain to be qualified.

Upgrade CLOA2030-4-A: Extending the Band 1 observing frequency to 52+ GHz is possible, as demonstrated on the LS #6 (S/N 105), requiring only modest upgrades (firmware and a COTS CVR) to each existing subarray, followed by complete PAI qualification testing.

7.3 Laser Synthesizer Improvements

The supplier of the LS and LORTM units (Teraxion) was commissioned to identify improved laser sources. In particular, the newly developed DFB lasers, offering native 8 kHz linewidth (with 300 Hz linewidth achievable with an improved noise reduction circuit) were evaluated. However, the survey and measurements yielded an unanticipated outcome: not only did the current manufacturer discontinue its DFB laser offering, but the alternate sources are not as good as the existing units. So, while ALMA will have access to spares suitable for repairs (LS as well as LORTM), improved performance using the current architecture is questionable. As the laser synthesizer modules age, adjustment margins needed to simply maintain performance are shrinking, and improvements are no longer viable.

Simply increasing the tuning speed is not a straightforward matter either. The CVRs need a minimum settling time when tuned over larger ranges, and the LS PLL might not be able to track a moving reference signal. There may be some significant improvements to be gained by pre-tuning the lasers before a frequency switch is called for. This aspect will need to be investigated further.

7.4 Alternate LO Schemes

As explained in sections 4.3.2 and 7.3, the two modules, ML and LS, which form the basis of the existing LO reference generation system, are still among the best ones that can be procured. Consequently, new and radically different LO time and frequency transfer schemes need to be studied. In particular, if the new baselines are to be populated by significantly different antennas than the current baseline ones, then a different LO architecture could be deployed (recall that the CLOA has an available sixth subarray slot available for science, already configured with EDFAs and connections to the AOS patch panel), such as:

- 10^{-13} – 10^{-16} frequency stability of 10 MHz reference achieved over 100 km (van Tour, Koelemeij, NRAO internal memo) using White Rabbit + PLL + OCXO: this would allow the development of a Direct Photonic LO approach, where the tunable LO would be generated at the antenna instead.
- The LO timing architecture being developed by Shillue (NRAO) and Kiuchi (NAOJ) for use with the Next Generation Very Large Array (ngVLA)

Upgrade CLOA2030-4-B: The Laser Synthesizers (LS) and LO Reference Test Modules (LORTM) are reaching the end of their planned lifetime (20 years). The AMA project should actively start procuring new units, or searching for alternatives.

8. Conclusions

This study has shown that the CLOA system, holistically designed to meet a very wide range of specifications, cannot necessarily accommodate substantial increases in performance. Wherever possible, a certain amount of “future-proofing” was included in the original design (such as keeping the original eighty antenna outputs, or “baking in” wider tuning margins for the LS), resulting in some of the ALMA 2030 goals being more readily achievable, either with respect to time, cost, or both.

The two major goals which still do not have viable upgrade path (i.e. increasing the baselines and improving the LO efficiency) are both associated with the availability of new/improved laser units: the fixed Reference Laser (ML) and the tunable Laser Synthesizer (LS). Both were supplied by Teraxion almost twenty years ago. After an extensive search, it was concluded that they remain representative of a high watermark for what can be achieved by current technology. Increasing tuning speed, or reducing the overall noise would require new technologies and architectures, implying a lengthy and expensive upgrade process. However, given that these units are approaching their planned end-of-life operating window, serious thought must be given to exploring a new generation of photonic LO sources.