Description and Cost Benefit Analysis of Proposed Enhancements to ALMA

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Abstract

The Atacama Large Millimeter Array, or ALMA, is a conglomerate of 66 giant antennae located in the Atacama Desert of northern Chili. Through advanced computing, these antennae work together as a single telescope to pick up radio signals from stars, planets, or other galaxies. Since beginning operations in 2011, ALMA has played a major role in scientific discoveries propelling the field of astronomy. With ALMA's extreme sensitivity and resolution, astronomers have been able to create 3-D mappings of molecular clouds, produce detailed images of protoplanetary formation, peer back over 13 billion years ago to the very first galaxies, and make many other astounding discoveries. Although it is stunningly cutting edge technology, ALMA could benefit from updates in order to ensure that it continues to provide the field with as many discoveries in the future. There are many proposed improvements to ALMA; this report focuses on four. The first, ALMA's correlator chip, a vital part to any modern radio astronomy array is over 10 years old. In terms of computing power, it is orders of magnitude behind newer chips. Replacing the correlator chip could double ALMA's bandwidth. The second, ALMA does not have a Band 2 receiver, which could be used to study the emission of high-redshift galaxies, deuterated molecules in cold gas, and a wide range of other applications . The third and fourth pertain to the Band 6 receiver, as well as the Band 3-8 receivers. These receivers produce undesirable noise temperature profiles and variations in gain. By altering the front-end configuration of the receiver and enhancing the amplifier system, these issues could be alleviated.

Overview

ALMA is not a single telescope, but an array of 66 telescopes that act as a single unit. By combining the observing power of a large array of telescopes, ALMA is able to view images with the same resolution as a telescope with a diameter equal to the separation of each telescope in the array. To turn radio waves into usable information, ALMA is first focused on an astronomical object, which is emitting in radio. Long radio waves are then collected by the array, and funneled through a series of waveguides. This first separates the light into two orthogonally polarized components, and the polarized light is funneled into an antenna. The electromagnetic wave causes the electrons in the antenna to oscillate, creating a change in voltage, or signal. This signal then reaches a receiver, which is used to manipulate the signal to a lower frequency. Once the signal is a lower frequency, it can be amplified while still providing useful information. Once the receivers process the signal, it is passed on to amplifiers, which make the signal stronger. This amplified signal is then sent to a correlator chip, which takes the discrete set of voltages constituting the signal from all of the receivers, and transforms them into information that astronomers can use.

Receiver upgrades

Overview

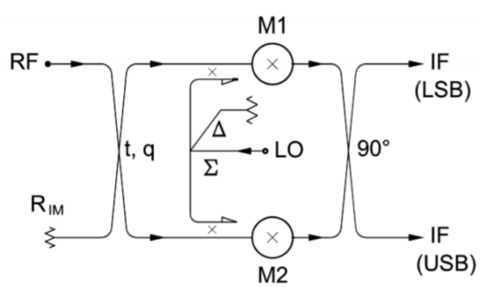
ALMA utilizes a superconductor-insulator-superconductor (SIS) receiver, which is an electronic receiving device used for radio astronomy to detect electromagnetic radiation. An SIS is composed of two superconductors separated by a thin insulating layer. A high frequency radio signal (RF) from a celestial object is focused onto the receiver. When the RF signal from the astronomical object is focused on the SIS receiver, it excites electrons and assists them in undergoing quantum tunneling through the insulating layer, producing an electronic signal corresponding to the frequency of the RF. Simultaneously, a local oscillator (LO) provides a different frequency. Next, the difference between the two frequencies is detected by a mixer. After the signal passes the mixer, a new intermediate frequency (IF) is derived. The IF is a much lower frequency than the original signal, meaning that each amplifier can provide more gain, and a stronger signal. The receiver is contained in a cartridge, and is sensitive to a different band of frequencies. Each of the ten band cartridges contain a system for receiving the incoming radio waves, the receiver, the LO, and amplifiers.

Band 6 SIS receiver improvements

Front end configuration

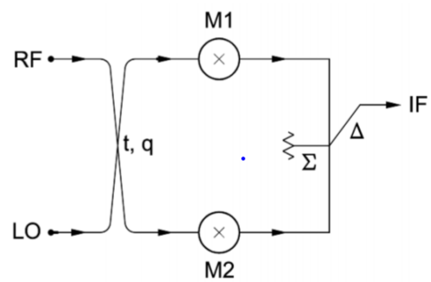
ALMA's current front-end configuration in band 6 uses a 90-degree sideband separating input hybrid (See Figure 1).

Figure 1: 90-degree input hybrid



The RF port is the signal from the celestial object being studied. LO is the signal from the local oscillator, which is pumped in to the mixer. M1 and M2 are mixers, which take the difference between the two frequencies. The signals from M1 and M2 are phase shifted by 90-degrees producing two sidebands—the lower (LSB) and upper (USB). These two bands constitute the IF. This phase shift is well suited for the type of RF input received. However, this process generates an unwanted third signal, the image frequency. The image frequency can degrade the quality of the data, requiring extraction at a later time. This is a source of variation in noise quantified by the noise temperature. The variation in noise temperature makes it much harder to differentiate between real astronomical data, and what is noise inherent to the system. The proposed solution to this detrimental image frequency and noise variation is to use a balanced sideband separating mixer, where a 90-degree input hybrid (Figure 1) feeds into two balanced mixers (Figure 2). This would not eliminate the image frequency. Instead, it would separate it from the real, useful frequency, hence lowering the amount of systemic noise produced by the receiver.

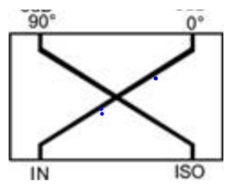
Figure 2: Balanced mixer



IF amplifiers

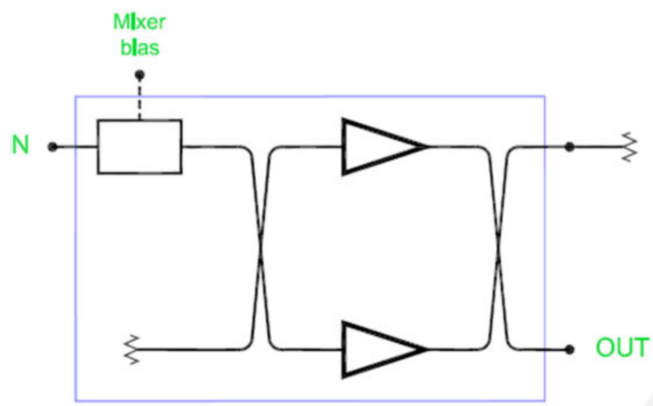
Once the IF signal is produced, it passes through a preamplifier. The preamplifier strengthens the weak IF signal, making it more noise tolerant and able to be processed more easily. The current ALMA preamplifiers have very low noise temperatures and work quite well. However, the produced gain curve varies significantly with frequency, which makes data manipulation more time consuming. The variation is produced by the interaction between the signal from the mixer and the input of the amplifier. Excluding this interaction would eliminate the variation in gain. This is currently done using ferrite isolators, which create rotating magnetic fields, forcing all of the signal to flow towards the port. The ferrite isolator may still add significant loss to the IF signal strength, in addition to the problem of bulk, being too large to act as a receiver cartridge. The proposed solution to this is to replace the current amplifiers with balanced amplifiers. These balanced amplifiers are composed of two identical, Low-Noise Factory (LNF) amplifiers in parallel, with inputs and outputs connected by a quadrature hybrid coupler. (Shown in Figure 3) The first hybrid coupler splits the IF signal into two parts, phase shifted by 90-degrees, and the second one recombines the amplified signals. This system would also eliminate the interaction between the signal and the amplifier ports. See Figure 4 for diagram of the full proposed system[4].

Figure 3: Quadrature hybrid coupler



A diagram of the proposed system is shown in figure 4

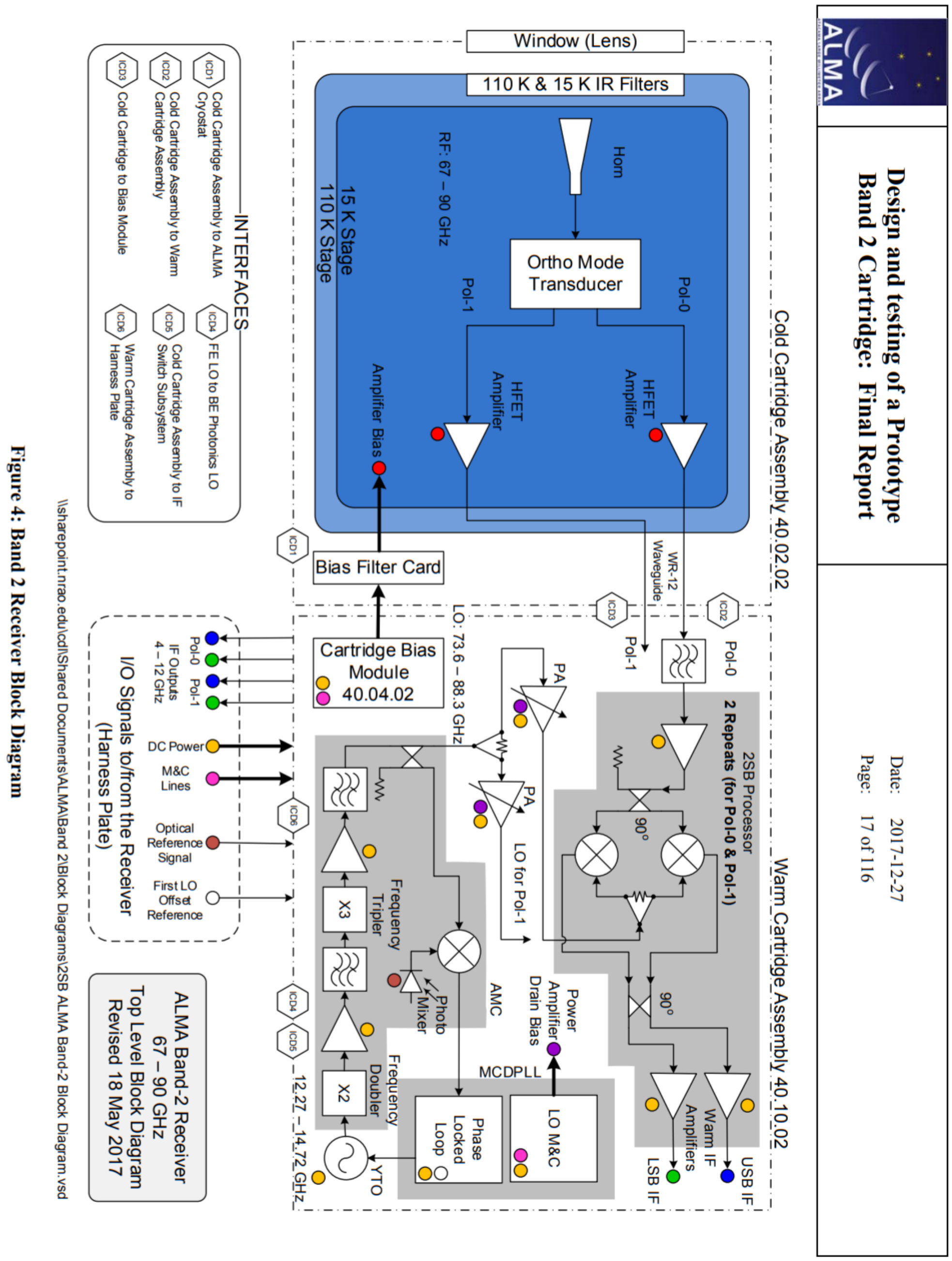
Figure 4: Balanced amplifier



Band 2 cartidge

The ALMA Band 2 cartridge serves a similar purpose as the system described in Section 1.2. It converts signal from 67-90 Ghz to an IF band from 4-12 Ghz. The input signal is linearly polarized, and the two polarization inputs are converted to four outputs (2 lower and 2 upper sidebands). The layout of the Band 2 cartridge is shown in Figure 5.

Figure 5: Band 2 receiver



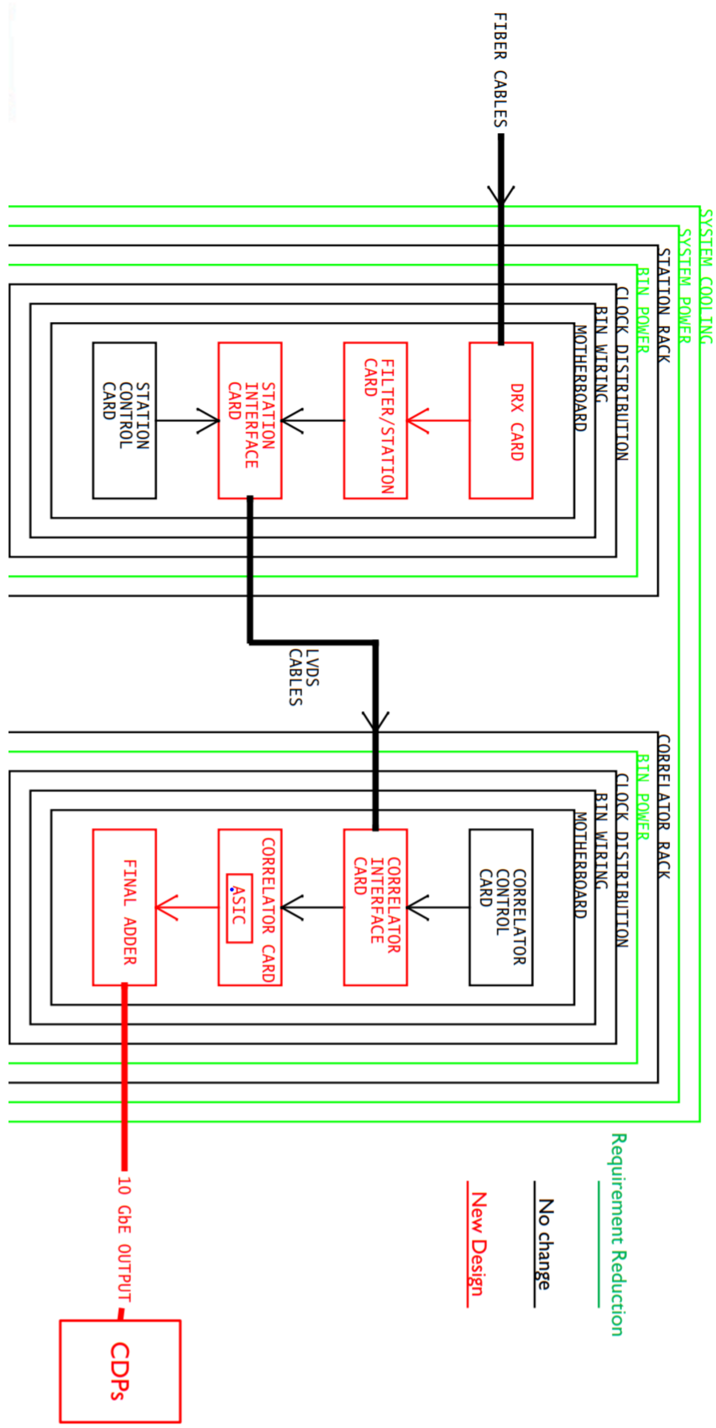
The cold cartridge assembly is surrounded by a vacuum seal. A lens is located on the outside of the room temperature window so that all of the incoming radio signal will go through the 110K filter window. There are three interchangeable lenses, each with a different focal length. These lenses are coated in a thin dielectric layer. Light passes through the lens and subsequently through the filters, which block infrared light. This filtration protects the data from distortion due to infrared rays, and also prevents the light from warming the cold cartridge section. There are two filters, one at the 110K stage of the cold cartridge and another, more stringent filter at the 15K stage. The horn antenna collects the light once it passes through the 15K filter. First, the horn funnels incident radiation using waveguides. The radiation then enters the narrow end of the horn, with parallel walls, which lead to the orthomode transducer. The transducer uses a turnstile junction to split the radiation into two orthogonally polarized components. The polarized light then reaches an antenna, and causes the electrons in the antenna to oscillate, producing electrical signal. The two polarized signals each pass through an heterostructure field effect transistor (HFET) amplifier. The HFET consists of two different materials with differing band gaps. The initial stage consists of a highly doped material with a wide band gap, causing the signal to move slowly. The second material is non-doped with a narrow bandgap, causing the electrons to flow very quickly when they pass from one material to the other. This difference creates a gain in signal. Next, the signal enters the warm cartridge. Here, it follows a process similar to that described in Section 2.2. The receiver produces an IF signal, which is then amplified again. The production of the IF requires LO, consisting of three basic modules. The first is the YIG oscillator (YTO), which creates a signal from 12.4-14.7 GHz. This signal then goes through the active multiplier chain (AMC), which multiplies, filters, and amplifies the YTO signal to the final warm frequency. The AMC also mixes the generated LO with the millimeter phase reference from the photo-mixer. The power amplifier (PA) module is then used to divide the LO signal into two channels and amplify both signals independently. Lastly, the signal is sent into the processor to work with the RF signal and produce the IF.

ALMA correlator enhancement

The correlator chip is the heart of all modern radio telescope arrays. It converts the voltages produced from the signal of the receivers into a cross correlation function. Unlike instantaneous voltages, the cross correlation function can be integrated without degrading the signal. The function can also be transmitted to a computer at a much lower data rate. According to the Wiener-Khinchin Theorem, the Fourier transform of the cross-correlation function represents the power spectrum—power as a function of frequency. Therefore, it is vital that the ALMA correlator functions properly. ALMA's current correlator is over 10 years old. According to Moore's law, the number of transistors in a microchip, analogous to computing power, grows at an exponential rate. As such, ALMA's current chip is several orders of magnitude behind modern technology.

Correlator design

Figure 6: Correlator design



In order to not disrupt the regular operations of the telescope, it is imperative that the design of the new correlator alter as little as possible. The system cooling, system power, and bin power requirements would be removed. The signal is sent to the chip station using fiber optic cables and received by the DRX interface card, a digital plug-in board used for fast data transfer. The DRX card then sends the data to the filter card, reducing the potential sources of error. The filtered signal then goes to the station interface, which transmits the signal to the correlator interface card. Next, the signal is sent to the applied specific integrated circuit (ASIC) correlator card, the most critical and costly component of the project. The ASIC card rapidly digitizes the analog signals and synchronously cross correlates and serializes the signal from all of the antennae. The data is sent to the final adder and prepared for post-processing in 10 gigabit (Gbt) ethernet form.

Cost benefit analysis

Receiver upgrades

Front end improvements

There is no public data on the cost of an SIS receiver, therefore the monetary cost of the proposed front-end configuration are estimated as an aggregation of the individual prices of its component parts. All dollar amounts are United States dollar estimations gained from supplier quotes. For the SIS configuration, one hybrid coupler is needed (maximum cost of $1,500), as well as two balanced mixers ($3,000 each), and two mixers for the 90 degree input hybrid ($1,500 each). These components total to roughly $9,000. Including labor cost of installation, the expected total cost is around $15,000. The most notable benefit of this installation is the reduction of noise temperature on Band 6. This design could be successfully implemented across Bands 3-8 as well.

IF amplifiers

Six suppliers provided price quotes for the required pair of LNF amplifiers. The lowest quote was $13,000 for the two LNF amplifiers. The two hybrids used in this system cost $1,500 each, for a total of $16,000. Accounting for installation labor costs, the expected total cost is around $22,000. At this price, the benefits of reduced gain variation far outweigh the costs of installing the new amplifiers.

Band 2 cartridge

ALMA Band 2 is comprised of frequencies from 67 to 90 Ghz, a little studied regime. By adding Band 2 capability, several key objects can be studied. High redshift emissions from dense molecular gas can be studied using Band 2, allowing astronomers to track HCN in these far away clouds. HCN is a strong indicator of star formation, particularly ongoing starbursts. Several deuterated molecules, present in protostars, emit in the Band 2 regime. By observing these deuterated species, astronomers can measure the age and evolution of large protostars. Deuterated molecules can also be used to to detect cosmic-ray irradiated gas, which in turn can be used to track the ionization of gas in distant galaxies. ALMA Band 2 could also be used to follow the evolution of dust into planets, as dust emits thermally in Band 2. For these reasons alone, there is a considerable benefit to installing a Band 2 cartridge.

Correlator upgrade

The correlator upgrade is a massive alteration to ALMA, and as such it is significantly more expensive than the other discussed proposals. The preliminary estimation of cost, per Lagasse's 2015 presentation, is approximately $7,000,000. Further, system integration will take a year, and installation a month, causing a serious disruption in telescope operations. The installation of the chip will change very little in regard to hardware. However, designing a system to test it will be very difficult. A minimum of a month downtime for testing the update would represents a large opportunity cost. A full month without the ability to acquire scientific data is also significant with no known cost attributed to this lost opportunity. However, the correlator upgrade would double the bandwidth and increase the resolution significantly. Since larger spectra can be observed at once with the correlator, efficiency will be improved, requiring fewer bandpass calibrations. In the long run, updating ALMA's dated correlator will allow for ALMA to remain relevant and continue to produce cutting edge discoveries, and aid in meeting ALMA's 2030 goal of doubling bandwidth.

Conclusions

Two of the four discussed proposals to enhance ALMA would provide an inexpensive solution to access cleaner, more manipulatable data. These two, the change in the Band 6 receiver front-end configuration and amplification system, will provide a tremendous value to astronomers compared to the monetary cost of the upgrades. The next discussed upgrade, the proposed Band 2 cartridge design, would allow ALMA to better observe dust, deuterated molecules, and objects at very high redshifts, among other potentially important astronomical discoveries. It is the author's opinion that no price is too high for a Band 2 cartridge, as a plethora of important discoveries must be hidden in the 67-90 GHz regime. The final proposed upgrade to ALMA is a massive overhaul to the correlator chip. This would not only allow for the doubling of bandwidth, but also improve temporal resolution (the rate of data) by a factor of 16. Such an improvement would allow astronomers to better observe the sun and pulsars, as well as other astronomical objects. Additionally, ALMA would be more equipped to resolve narrow spectral lines, allowing for it to better probe infalling gas in collapsing cores. However, as this upgrade costs well over $7,000,000 as well as a month of installation time, this is the most high risk of the proposed upgrades. Contrarily, a month of downtime is surpassed by years of improved science capability. It is of the author's opinion that approval of the proposal to Band 2 would be of the greatest benefit to the perpetuation of ALMA as a purveyor of discovery. However, ALMA would greatly benefit from any of the aforementioned alterations.

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