ALMA Correlator Upgrade Science

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1. Summary of Science Benefits from the Correlator Upgrade

The upgrade of the ALMA correlator will be staged, in order to provide benefit from the more straightforward parts of the upgrade which involve little or no additional hardware.

In Phase 1 the upgrade will enable increased channelization (resolution and spectral grasp) and sensitivity (4bit vs 2 bit). Although these may require an archive upgrade for increased data rate, current modes are supported and the current data rate could be maintained should that be desireable for operational reasons. In Phase 2 the upgrade would enable a bandwidth increase to 8 GHz x 2 SB x 2 polarizations. This, of course, requires additional hardware implementations, including the backend Intermediate Frequency Interface, the digitizers and Digital Signal Processing and the antenna to AOS Technical Building fiber data links. Upgrades to these systems are under study a plan for advancing from Phase 1 to Phase 2 will be developed.

ALMA science will benefit from an upgraded correlator in several ways. The first three of the following occur in Phase 1, the last two in Phase 2.

- ALMA's instantaneous spectral grasp is increased–for narrow-lined objects which need fine resolution, as wider spectral windows may be imaged.
- ALMA will meet its specification for resolving thermal line widths in cold contracting cores at its lower implemented frequencies; currently this specification is only met at 211 GHz and higher frequencies using uncommissioned 'twice Nyquist' correlator modes.
- In the upgraded correlator proposed here, where the broadest spectral coverage or highest spectral resolution is not needed, 4-bit x 4-bit and double Nyquist modes could be used, providing higher efficiency observations. Use of sensitive 4-bit x 4-bit modes, made more accessible with the upgrade, would cut integration times 12 % (for the full array, the equivalent of an increase of eight antennas in collecting area).
- Band 6 currently can present more bandwidth to the correlator than it can process, also true of the prototype B2 cartridge resting at CDL and a possible B9 2SB cartridge for which a prototype is deployed at APEX. One goal of the upgraded correlator is to increase the bandwidth processed by the correlator by a factor of two to 16 GHz x 2 polzns. Broader spectral windows also provide additional continuum sensitivity; an important advantage in high frequency bands, for which calibrators tend to be scarce and weak. Broad windows also increase the depth to which a deep field, for example, might be imaged in a given time. A spectral survey might be undertaken more efficiently owing to the increased bandwidth, as relatively less overhead is needed for calibrations.

- High time resolution would be available for measurement of solar events, pulsars or fast transients.

In the following, we order the science benefits in an order which may be implemented progressively in stages. First we detail items (subsections 1-3) which may be implemented with little additional hardware. Some correlator upgrades provide additional benefits, such as bandwidth, which will take advantage of new wideband receivers under development, and new digital hardware.

1.1. Improved spectral grasp at high spectral resolution

Currently, the commissioned correlator modes include eight dual polarization modes, one with coarse frequency resolution in Time Division Mode (TDM; used normally for continuum) and seven in higher frequency resolution Frequency Division Mode (FDM). Each of the FDM modes offers 3840 channels across bandwidths chosen from 1875, 938, 469, 234, 117 or 58.6 MHz total width. The default Hanning weighting then limits spectral resolution to values between 0.03 MHz (0.1 km/s at B3) and 0.976 MHz. (3.3MHz at B3). In the higher resolution of these two modes, appropriate to dense starless cores for instance, the total bandpass at 86 GHz encompasses only 197 km/s, or about 3% of the bandpass. One may have four spectral windows but still only 3% of the total bandpass is covered by the correlator windows at highest resolution. For sources with relatively narrow spectral lines, such as most galactic sources, a spectral survey with such a limited bandpass would be prohibitively time-consuming, as each spectral setting necessitates additional calibration, a substantial overhead.

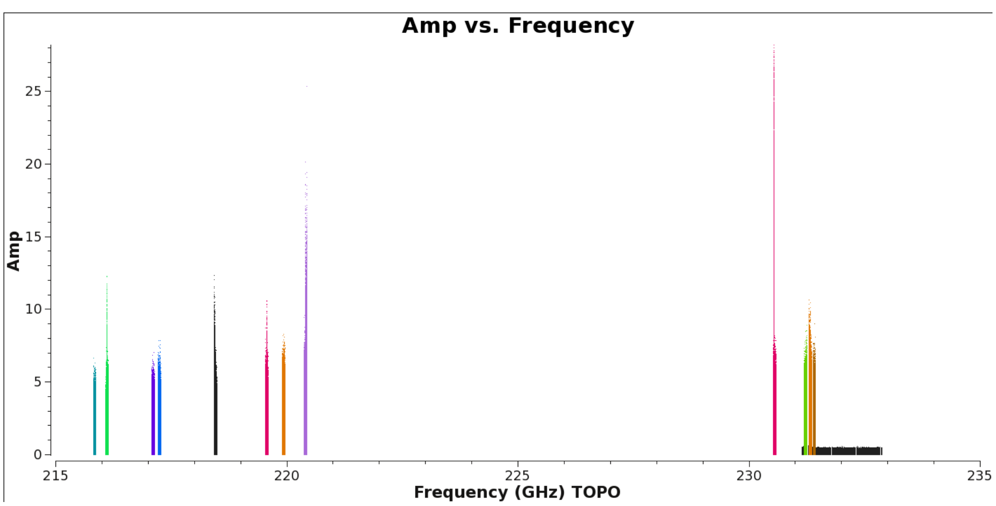

Fig. 1.— Typical protostar/protostellar disk spectral setup for ALMA. Cold gas probes the molecular envelope and disk. Modest masses limit kinematic linewidths. As a result, the science requires high resolution (a low resolution continuum window is also needed, shown in black, for calibration). The twelve high resolution windows, of bandwidth 58MHz, cover some important lines, but many important lines cannot be covered with the current correlator capabilities.

With the proposed correlator upgrade, the same set of currently available modes are

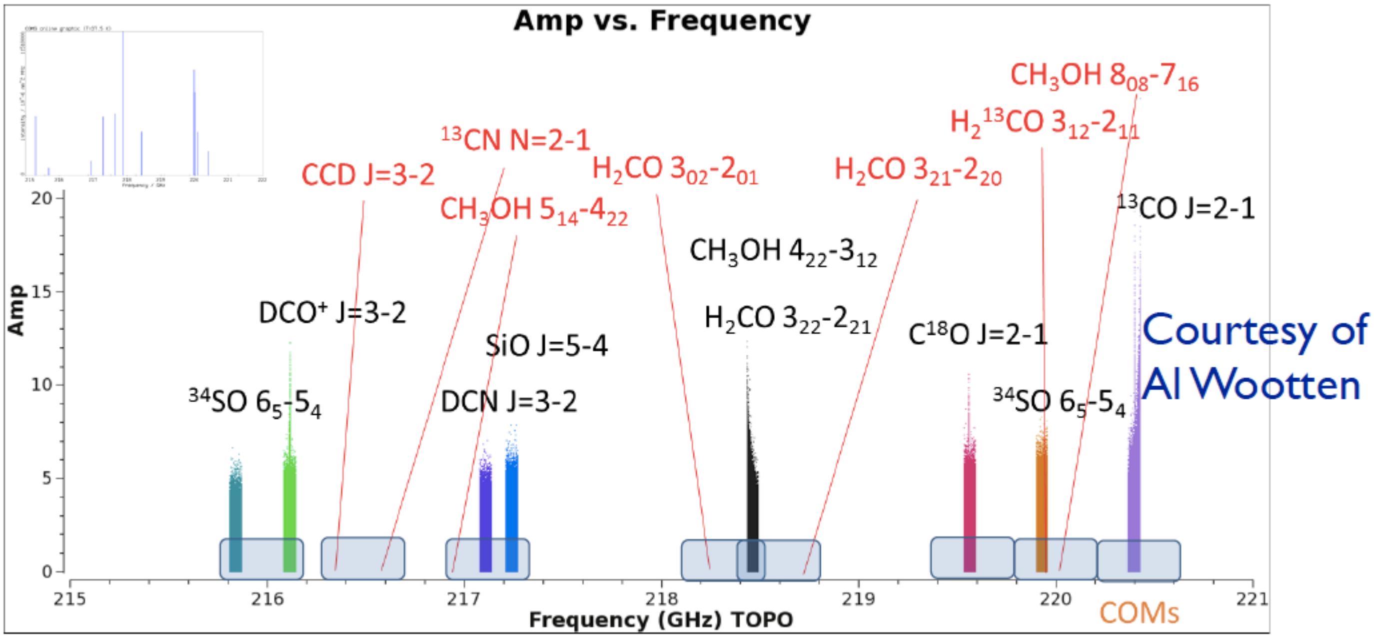

Fig. 2.— Typical protostar/protostellar disk spectral setup for ALMA using the upgraded correlator. Many more important lines (red) can be covered with the upgraded correlator capabilities.

enhanced: each FDM mode offers 16384 channels with cross polarization products in two baseband channels across bandwidths chosen from 3750, 1875, 938, 469, 234, 117 or 58.6 MHz total width. Therefore, for example, **a spectral survey of an entire 2 GHz bandpass could be made to a resolution of 0.2 km/s with a single frequency setting of a spectral window**. Such a capability would enlarge scientific discovery space, by enlarging the spectral grasp of the instrument, increasing the information delivered to the Principal Investigator and to the archive. Additionally, spectral resolution at ALMA Band 1 (35-51 GHz) would be 0.03 km/s over a 500 km/s wide window. Many energetically low-lying lines occur in this band which would be excited in the cold outer envelope of cores forming stars. This would allow resolution of and comparison of multiple lines. For instance, the J=4-3 line of HC_3N at 36 GHz, the hyperfine components of which have been used to measure thermal and non thermal motions within dense cold clouds, and the J=2-1 lines of CH_3CN, which has been used to probe cloud temperature. Through intercomparison of line profiles at different energies, the physics and kinematics of the infall envelope may be measured.

As a specific example, consider an observation of a protostar and disk in ALMA Band 6 using a spectral setup similar to ones employed by many investigators. A variety of physical conditions are found in the environments of protostars. Spectral lines conveying chemical and kinematic information on these conditions arise from components of the collapsing dense interstellar cloud or filament, the disk or pseudodisk in the immediate environment of the protostar, and the transition regions between these components. An example of an ALMA spectral setup is shown in the Figure. Current correlator resources are insufficient to cover all of the lines of interest in the characterization of the protostar and its evolving environment. An example of a setup with the upgraded correlator is shown in Figure 2, providing more extensive spectral coverage (in this case mode 47, with four times the spectral grasp, at higher 4bit efficiency, with double the velocity resolution).

1.2. Higher spectral resolution

One class of interesting narrow lines are those which have self-absorption which indicates infall ("infall asymmetry", Fig. 1 (cf Evans et al. 2015)). ALMA requirement SCI-90.00.00.00-030-00 states 'It shall be possible to configure the correlator to achieve sufficient resolution (0.01 km/s) at 100 GHz to resolve thermal line widths', one purpose of which is to resolve the linewidths of cold infalling material.

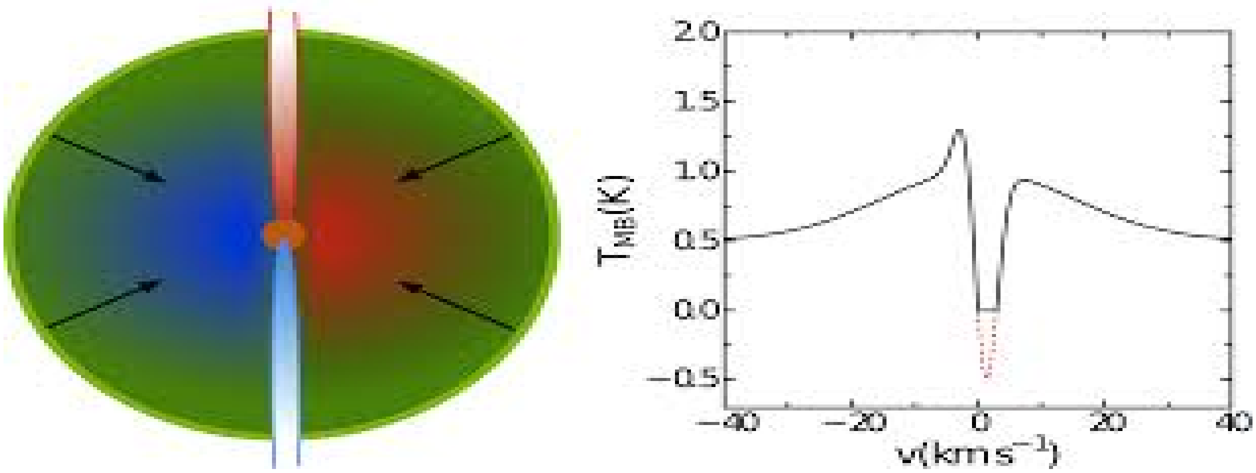

Fig. 3.— Infall Cartoonâfor First Hydrostatic Core candidates envelope. Material along the line of sight falling onto the protostellar core is redshifted for the observer; that material is cold gas in outer regions of the core. Through resolved observations of various transitions, observations of infall provide a valuable probe of the physics of the outer envelope of the core.

In that case the minimum number of channels across the line needed to model the line properly increases, from perhaps 2 resolution elements = 1 sigma for a simple gaussian line to something like 4 resolution elements = 1 sigma for a line with a dip or a red shoulder. If one applies these criteria to an extreme case (low frequency, heavy molecule, low temperature), then one should consider e.g. the HC_3N line at 100 GHz, in a cold, slowly contracting starless core with a central temperature of 8 K. The thermal velocity dispersion would be 0.036 km/s and so the spectral resolution should be about 0.018 km/s to resolve a gaussian line or 0.01 km/s to resolve a self-absorbed gaussian line. ALMA does not currently meet its specification for resolving thermal line widths in cold contracting cores at its lower implemented frequencies at 85 GHz and falls further short for frequencies as low as 35 GHz, for which receivers are now under construction. At 85 GHz with a correlator upgraded as proposed here, the resolution would reach 0.013 km/s, meeting the requirement. Further improvement could be achieved by employing different smoothing functions than the default Hanning smoothing.

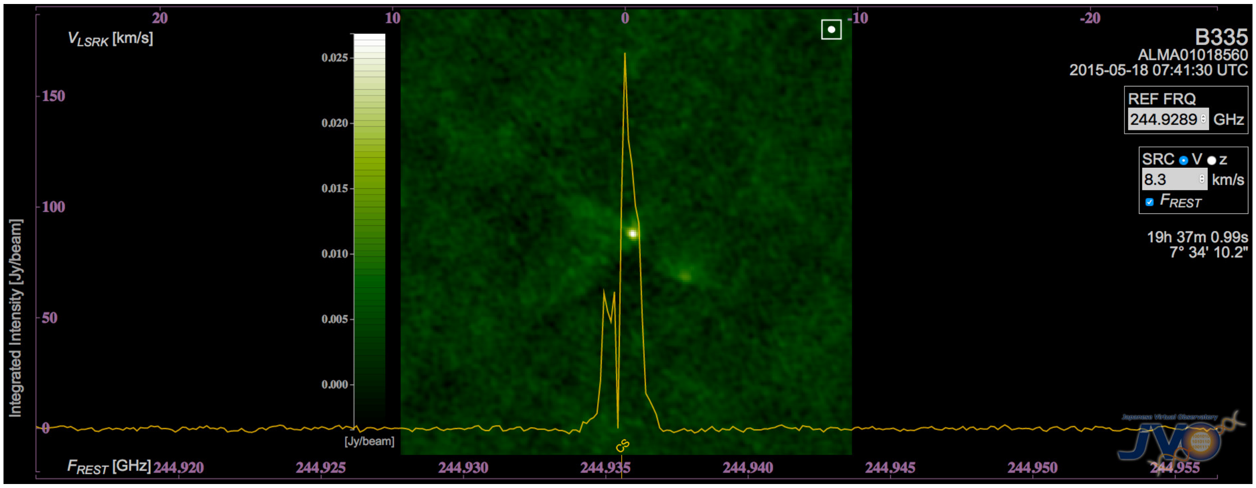

Fig. 4.— ALMA archival data showing the 1.3mm CS J=5-4 line in the envelope of collapsing core B335. Note the apparent complex structure, barely resolved, providing details on the physics and kinematics of the infalling material. Lower excitation lines at lower ALMA frequencies would provide insight into the nature of infall (the axes are reversed in this image, for which frequency lies on the abcissa compared to that in Figure 1). The correlator upgrade would provide the necessary resolution to investigate the kinematics of the cold infalling material.

1.3. Increased sensitivity, decreased observing time

The efficiency of observing the larger bandwidth may also improved by the use of the double Nyquist mode. Using 4-bit x 4-bit modes and/or double Nyquist mode (95% efficiency versus 85% including the effect of the 3-bit sampler) is equivalent to adding about 8 antennas to the array or cutting integration times down by 12%. Owing to the details of the way correlator resources are deployed to use these modes, the bandwidth over which they can be used is limited. For example, in a 'continuum' low resolution mode, half the bandwidth would be available (though in 2bit x 2bit modes, the full bandwidth is obtained).

1.4. Broader bandwidth, additional spectral grasp

The upgraded correlator has twice the spectral grasp of the baseline correlator, that is, 2 sidebands x 8 GHz x 2 polarizations, or 32 GHz as compared to 16 GHz for the baseline correlator. For science projects which require maximal spectral coverage, such as spectral surveys or detailed study of line-rich sources, this provides a substantial advantage. In Figure 3, a Herschel/Hexos spectral scan of most of ALMA Band 9 in Orion South is shown. The baseline correlator could cover the 8 GHz window shown in yellow, containing the isotopic CO J=6-5 lines. The upgraded correlator will cover that window in addition to the window shown in blue, containing a number of weaker lines of $C^{17}O$ and more complex molecules, such as methanol, formaldehyde and CN. To cover both windows with the baseline correlator would require two spectral settings, with substantial calibration overhead. Only one bandpass calibration need be made per spectral setting, rather than several, for the upgraded correlator.

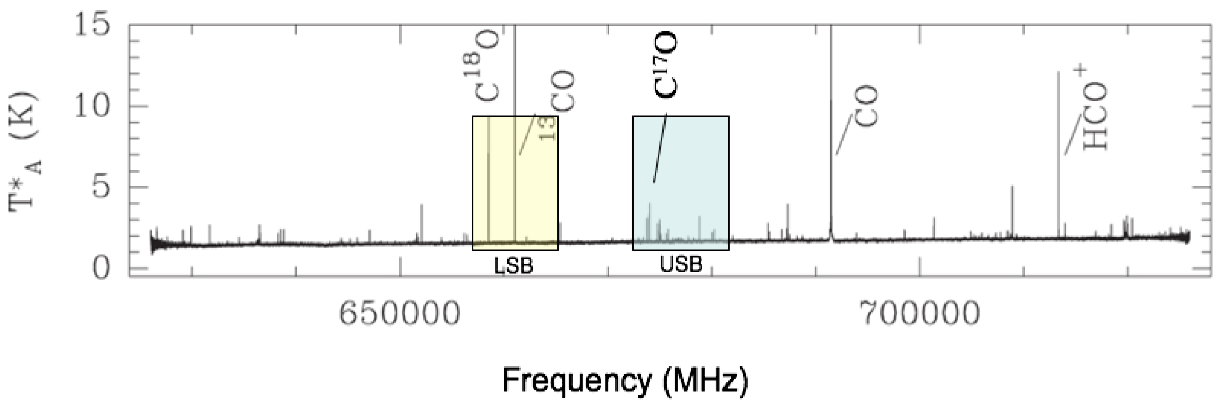

Fig. 5.— A part of the Herschel HEXOS spectral scan in a portion of ALMA Band 9 (611-720 GHz) showing the spectral grasp of the current baseline correrlator (8 GHz x 2 polarizations) compared to that from the upgraded correlator (2 x 8GHz x 2polarizations). From Analysis of the Herschel/Hexos Spectral Survey Toward Orion South: A Massive Protostellar Envelope with Strong External Irradiation K. Tahani et al. 2016 ApJ 832.

Spectral searches benefit from the increased spectral grasp of the upgraded correlator also. At present one ALMA receiver covers bandwidths which exceed the 2 x (2x2)GHz x 2polarizations = 16GHz capacity of the baseline correlator: Band 6, with its current 5-10 GHz IF, produces 5GHz x 2 polarizations x 2 sidebands, or 20 GHz. A 2SB upgrade to B9 is being tested at APEX which would allow access to the whole 32GHz; a similar upgrade study was proposed to NA. Studies are under way to upgrade the signal digitization so that increased receiver bandwidths may be conveyed to the correlator. Studies have been published which detail upgrade paths to increased bandwidths for Bands 2^+ (Bryerton et al 2013), 2+3 (Fuller et al 2016, Beltran et al 2015), Band 3 (Henke et al 2017) and 6 (Kerr et al. 2016). In fact, the very sensitive Band2^+ receiver has passed a design review and could be produced for ALMA now while the Band 2+3 alternative will be reviewed soon. As an example of the improvement in spectral grasp for surveys, the ASPECS survey (Walter et al. 2016) used eight frequency tunings to cover the range of Band 6, each tuning with substantial calibration overhead. The upgraded correlator would only need four frequency settings to cover the same range, in substantially less time.

1.5. Higher time resolution

One could trade temporal resolution for spectral resolution, increasing the number of spectral points per baseband. An uncommissioned mode of the current corrlator provides time resolution of 1 msec for auto-correlation products and 16 msec for cross-correlation products. The addition of RAM to the correlator chip makes it possible to trade time resolution for spectral resolution on auto and cross-products, a new feature which could enable high time resolution spectroscopy of solar events, for instance. A current study (Cordes et al, in progress) should provide ALMA with a capacity for observing pulsars. ALMA's southern hemisphere

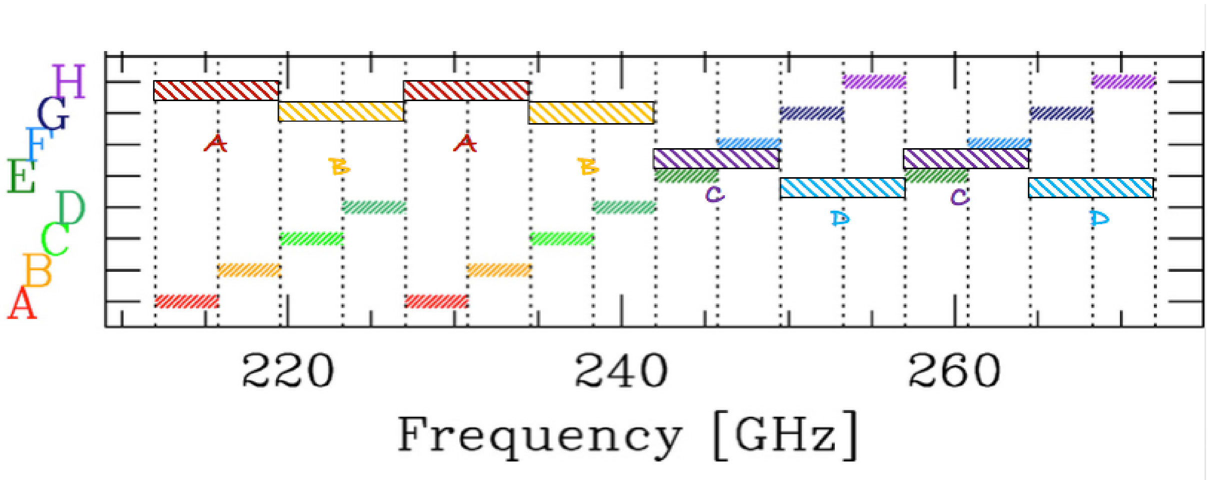

Fig. 6.— A diagram showing the eight Band 6 tunings (Lettered, left) needed to cover the frequencies of the [C II] line at redshifts of 6 to 8 in the ALMA ASPECS spectral scan of the Hubble UltraDeep Field. The eight settings needed using the upgraded correlator are shown in the upper bars, noted by script letters.

location makes it ideal for exploration of high dispersion sources near the Galactic Center, such as the recent magnetar outburst, which was observed at frequencies up to 291 GHz (Torne et al 2017). Fast transients provide another interesting possibility; ALMA provided 1.3mm upper limits for instance to the recent identification of FRB121102 (Chatterjee et al 2017).

For the Sun, both impulsive and oscillatory phenomena are expected on sub-second time scales as a result of impulsive energy release in flares. Quasi-periodic oscillations or pulses are seen in hard X-ray and radio emissions, as well as millimeter and submillimeter emission. Kaufmann et al (2009), for example, report peak pulse repetition rates of 5-10/s in 212 and 405 GHz observations of a powerful X-class flare observed with a time resolution of 5 ms. The origin of the mm/submm pulsations is not understood currently. Their location within a flaring source has not been determined, nor their relationship to OIR and X-ray time variations. The radiative loss time in the chromosphere is of order 2 ms and so a time resolution for correlated data of 1 ms is desirable. Recognizing the trades between time resolution, baselines, and spectral channel are likely necessary, reduced numbers of baselines and channels are acceptable. The data volume will probably still be extreme. Fast sampling could be implemented as a rotating data buffer or it could be triggered by a total power threshold.

2. REFERENCES

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