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The Most Important Frequencies for Astronomical Polarization Measurements in ALMA Band 6 (211-275 GHz)

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T. R. Hunter & C. L. Brogan

0. Abstract

Knowledge of interstellar magnetic fields requires accurate measurements of continuum and spectral line polarization in the millimeter/submillimeter wavelength range. Unfortunately, laboratory performance results from the pre-production phase of the ALMA Band 6 receiver (211-275 GHz) indicates that the specified polarization purity of the front end (99.5% = -23 dB) cannot be met across the entire band. It is therefore pertinent to consider the most important frequency ranges to obtain polarization purity from a scientific perspective. A review of the available spectral line transitions in Band 6 indicates that the two preferred regions are the range from **219–230.5 GHz** (LO = 225.47 GHz) and a small range close to **262 GHz**. The first range contains the most abundant molecule (CO) and its isotopologues which can be used to measure the magnetic field direction in the gas via the Goldreich-Kylafis effect. It also contains promising lines from the paramagnetic molecules CN and SO which offer the best chance to perform quantitative studies of the magnetic field strength via Zeeman splitting. Furthermore, because better polarization purity promotes higher dynamic range and fidelity in total intensity images, it makes sense to focus effort on this frequency range because a significant fraction of Band 6 observations will be made at (or near) the rest-frame CO lines. The second important frequency range is close to **262 GHz** which contains transitions of CCH which is another very promising paramagnetic molecule for Zeeman splitting measurements. We suggest that if the polarization purity can be shown to meet specification in these two ranges, then the requirement at 275 GHz can be relaxed. In any case, we suggest making future cross-polarization measurements at 262 GHz, rather than the current adjacent standard of 259 GHz.

1. Scientific and Technical Requirements Related to Polarization

For purposes of background (and for convenience), the following subsections contain all the relevant excerpts from various ALMA specification documents which illustrate the flow down of polarization requirements from Science to Front End. However, it was recently demonstrated (Hills 2008) that many of these specifications are regrettably loose and will make it a difficult task to measure the typically low (1%) polarization of interstellar magnetic fields. For example, the ALMA specification on the Front End polarization purity is only -20 dB (in power). By comparison, the cross-polarization performance of the EVLA at K-band ranges from 2%–5% in voltage (Perley & Sault 2009) which corresponds to -26 to -34 dB in power. Unfortunately, the effect of this level of leakage remains difficult to remove accurately (particularly the parallel-hand leakage correction) and will reduce the dynamic range, sensitivity, and fidelity of *all images*, including the total intensity images which every project will require (see the discussion in the context of Band 7 on EDM at Moellenbrock & Hills 2008). Thus, determining the best correction methods is a topic that requires significant research and development for both EVLA and ALMA (see e.g. Cotton & Perley 2010; Owen 2008). In light of these concerns, it is important for ALMA to achieve the existing polarization specifications over at least some portion of each band so that the calibration process can deliver the data products required to meet the science goals. For a detailed description of the proposed polarization calibration process for ALMA, please see Myers (2004). A good summary of the current cross-polarization performance of Band 6 is described in Effland, Schmitt, & Reynolds (2009). In general, the performance at the low frequency end of the Band is better than the highest frequency end.

1.1. General Science Requirements for Polarization Studies

From ALMA-09.00.00.00-001-A-SPE (released 2006-07-28):

- 310: It shall be possible to measure all polarization cross products simultaneously in interferometric and autocorrelator total power.
- 320: The error in polarized flux for a source where the circularly and linearly polarized fluxes are zero shall be no more than 0.1% of the total intensity on axis after calibration.
- 330: It shall be possible to measure the position angle to within 6 degrees.
- 345: Sensitive polarimetric interferometric observations require system stability in the independent polarization channels. To measure polarization accurately in interferometric mode to 0.1% levels requires a differential gain stability between the two polarization channels of better than 1×10^{-3} in 5 minutes, the typical time between which calibration of instrumental polarization can be performed. This applies to all receiver systems.

1.2. System-Level Technical Requirements

From ALMA-80.04.00.00-005-B-SPE (released 2006-09-21):

- 224: Cross polarization on axis (power) shall be < -30 dB below the desired polarization **after calibration**. Instrumental (Antenna and Front End) cross pol. shall be < -20 dB. The achieved cross pol. shall be stable to better than -10 dB over a polarization calibration cycle.
- 225: Cross polarization off axis (power) shall be < -30 dB (tbc) below the desired polarization at any direction in main beam down to the -10 dB (tbc) point **after calibration**. Instrumental (Antenna and Front End) cross pol. shall be < -20 dB. The achieved cross pol. shall be stable better than -10 dB over a polarization calibration cycle.
- 226: Cross coupling between polarization channels (power) shall be < -60 dB.

1.3. Front-End Sub-System Technical Specifications

From ALMA-40.00.00.00-001-A-SPE (released 2007-04-17):

- 226: The polarization efficiency of the tertiary optics system shall exceed 99.5% for all ten bands. This requirement simultaneously applies to both orthogonally polarized beams of a cartridge.
- 250: The nominal polarization state of the front end optics shall be linear.
- 255: For all frequency bands the Front End shall receive two orthogonal polarizations, designated “Polarization 0” and “Polarization 1”, with each one converted to one or more separate IF outputs depending on mixing scheme.
- 260: The E vector of the polarization channel designated “Polarization 0” shall be aligned to within 2 degrees of the radial direction of the cryostat.
- 265: The E vector of the polarization channel designated “Polarization 0” and the E vector of the polarization channel designed “Polarization 1” shall be orthogonal to within 2 degrees.
- 271: The, uncorrected, cross talk between orthogonal receiver channels, RF and IF, inside the front end shall be less than -60 dB. The receiver channel is defined as the signal path starting at the RF waveguide input of either the low-noise amplifier (Bands 1 and 2) or SIS mixer (Bands 3-10) and ending at the IF output of the FE assembly.

- 272: The co-alignment, on sky, between the beams of the orthogonal polarization channels of one cartridge shall be less than 1/10 of the Full Width at Half Maximum (FWHM) of the primary beam. This requirement is applicable for Bands 1 through 10.

2. Scientific Motivation for Polarization Observations

Although magnetic fields are thought to play a crucial role in astrophysics, and in particular the formation of stars, relatively little is known about their strength. There are three techniques available to measure the magnetic field in molecular clouds: (1) linear polarization of dust continuum emission, (2) linear polarization of spectral lines from abundant molecules, and (3) Zeeman effect splitting in the circular polarization of spectral lines from paramagnetic molecules. Each of these have positive and negative aspects. For example, both dust polarization and spectral line linear polarization can only directly measure the *direction* of the plane-of-sky magnetic field and only statistically the *strength* of the magnetic field (Chandrasekhar-Fermi technique) over size scales large enough to provide a statistically large sample of points (beams). In contrast the Zeeman effect directly probes the line-of-sight direction *and* strength of the magnetic field on size scales as small as the telescope resolution. Thus, both a linear and circular polarization technique are required to fully characterize the magnetic field. Additionally, (1) a number of currently uncertain non-magnetic effects may impact the degree of dust and spectral line linear polarization and (2) only spectral line linear polarization and the Zeeman effect can probe the magnetic field as a function of velocity. Therefore, because of the complementary nature of the three techniques, it essential that observation of all three be optimized. Since the degree of dust polarization is relatively insensitive to the exact frequency observed within a given band, in order to choose a frequency range at which to optimize receiver polarization performance in any given ALMA band, the best spectral lines for polarization measurements must first be identified in that band.

The most important molecule known to have detectable linear spectral polarization is CO and its isotopologues. The polarization mechanism is due to the Goldreich-Kylafis effect (Goldreich & Kylafis 1981) and is quite small – about 1%. The Goldreich-Kylafis effect was first detected in the ^{12}CO (2-1) transition (230 GHz) at the JCMT (Greaves et al. 1999). It is important to note that the level of spectral line polarization is maximized for transitions with optical depth $\tau = 1$ (Deguchi & Watson 1984; Goldreich & Kylafis 1981). Therefore, in order to explore deeply embedded regions (i.e. where stars form) the rarer isotopologues of CO will need to be observed. Furthermore, in order to explore the magnetic field as a function of velocity (i.e. across the line profile), it is often desirable to simultaneously observe several isotopologues of CO because ^{12}CO will exhibit $\tau = 1$ in the line wings while C^{18}O or C^{17}O or will approach $\tau = 1$ only at the central velocity where the gas column density is highest. The four frequencies of the main CO isotopologues range from 219.56 to 230.538 GHz and are listed in Table 1. All but the least abundant isotopologue ($C^{17}O$) can be simultaneously observed with an LO setting of 225.47 GHz, assuming that the Band 6 IF range extends down to 5.0 GHz (which is the subject of a pending specification change request: FEND-40.02.06.00-379-A-CRE). Another reason to prefer the best polarization purity at the CO lines is that a significant fraction of ALMA observations (regardless of polarization) will be performed on the CO lines in the Milky Way and nearby galaxies. Because better polarization purity also leads to higher fidelity images of total intensity, this choice will help maximize total scientific output of ALMA.

Unfortunately, there are relatively few molecules that are both sufficiently abundant and paramagnetic to be used to measure the Zeeman effect. Strong emission is important because, the Zeeman effect signal is typically only at most a few percent of the total intensity. For example, the CO molecule, being in the common $^1\Sigma$ electronic state, does not exhibit any appreciable Zeeman effect (e.g. Townes & Schawlow 1955). Thus, those few molecules with the right properties are extremely important. In the past, Zeeman effect studies have primarily concentrated on cm-wavelength neutral hydrogen (HI) and OH absorption lines (e.g. Brogan & Troland 2001; Sarma et al. 2000) and various cm-wavelength maser lines. While certainly providing valuable information, these studies suffer from the fact that thermal HI and OH emission does not in general trace the very high density gas where stars form, and maser emission is inherently tracing gas in an unusual (non-thermal) state. Fortunately, there are a few molecules that do have strong Zeeman coefficients and trace high densities ($\gtrsim 10^5$ cm^{-3}) in the millimeter/submillimeter wavelength regime (see Bel & Leroy 1989; Bel & Leroy 1998). Of these, the CN, SO, and CCH molecules are particularly promising since they are relatively abundant: $\sim 10^{-4}$ - 10^{-5} compared to CO (Bergin et al. 1997), and have high Zeeman coefficients (up to 2 Hz μG^{-1}). However, because the Zeeman effect depends on the inverse of the line width (measured in frequency units), millimeter wavelength Zeeman observations will require commensurately higher sensitivity than those at cm wavelengths. As a result, large millimeter telescopes are required.

Table 1: Transitions in Band 6 from the abundant molecule CO and its isotopologues (in order of decreasing abundance)

Species	Frequency (GHz)	IF (GHz)[a]
^{12}CO	230.538	5.068
^{13}CO	220.399	5.071
$C^{18}O$	219.560	5.910
$C^{17}O$	224.714	n/a

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[a] For an LO setting of 225.47 GHz, which provides simultaneous observation of 3 lines at the highest IF.

A few attempts have been made to measure the Zeeman effect at mm wavelengths, with for example the IRAM 30m in CN at 113.5 GHz (Crutcher et al. 1999; Falgarone et al. 2008) among others. However, these experiments have thus far produced somewhat disappointing results due to insufficient sensitivity and poor quality polarizers. ALMA will be an excellent instrument for molecular Zeeman studies given its very large collecting area and expected polarization stability. The 3 mm transitions of CN, SO and CCH (along with many others) have been mapped toward Orion A, M17SW, and Cep A (Ungerechts et al. 1997; Bergin et al. 1997). These studies found that SO is strongly enhanced toward the energetic BN/KL region of Orion A, while CN and CCH were moderately enhanced toward a more quiescent core about $3'$ North of BN/KL (Ungerechts et al. 1997). Toward low-mass prestellar cores, the abundance of CCH has been measured at 10^{-8} relative to H_2 (Padovani et al. 2009). A recent systematic survey of high-mass cores undertaken at the Caltech Submillimeter Observatory (CSO) of the Band 6 (~ 1.3 mm) lines of CN, SO, and CCH at $30''$ resolution indicate (somewhat surprisingly) that CCH is often the most spatially compact molecule of the three, suggesting that it is well-suited to interferometric follow-up (Brogan et al,. in prep.). Moreover, the isotopologues ^{13}CCH and C^{13}CH are also strong enough to detect (Saleck et al. 1994), meaning that the optical depth can be measured accurately.

CN is also of particular interest given its hyperfine structure (which provides the ability to measure optical depth) and the fact that it has a transition with the strongest Zeeman coefficient of the bunch. The line frequencies of these species in Band 6 are concentrated into two groups: CN (which can be observed simultaneously with ^{12}CO in USB at IFs of 6.18 and 9.82 GHz, respectively) and CCH and SO (which lie within ~ 0.2 GHz of each other near the top edge of the band at ~ 262 GHz). A second SO line can be observed as part of the ^{12}CO/^{13}CO/C^{18}O tuning. The frequencies, line strengths, and Zeeman coefficients of these lines are listed in Table 2. A few weaker transitions from these species (i.e. with line strength < -4.0) have been omitted.

3. Specific Recommendations

The frequency of the spectral lines discussed in Section 2 are overlaid with a model of the atmospheric transmission across the Band 6 tuning range in Figure 1. Given the proximity of the CO transitions to the CN transitions near the low end of the band, the highest priority frequency range to achieve optimal polarization purity is 219.5–230.6 GHz. One of the exact LO settings to consider is 225.47 GHz. The next highest priority is located toward the top of the band where CCH and SO can be observed simultaneously with an LO setting between 252.1–256.8 GHz. We suggest that if the Band 6 polarization purity can be shown to meet specification in these two ranges, then the requirement at 275 GHz can be relaxed. If good performance cannot be achieved in both frequency ranges, then Zeeman observations of CCH may be forced to use other bands. The $N = 1 - 0$ transitions appear in Band 3 (87.4 GHz), the $N = 2 - 1$ appear in Band 5 (174.8 GHz), and the $N = 4 - 3$ appear in Band 7 (349 GHz). In any case, in order to better assess the situation, we suggest making future cross-polarization measurements at 262 GHz, rather than the current (adjacent) standard frequency of 259 GHz (see Fig. 2 of Effland, Schmitt, & Reynolds 2009).

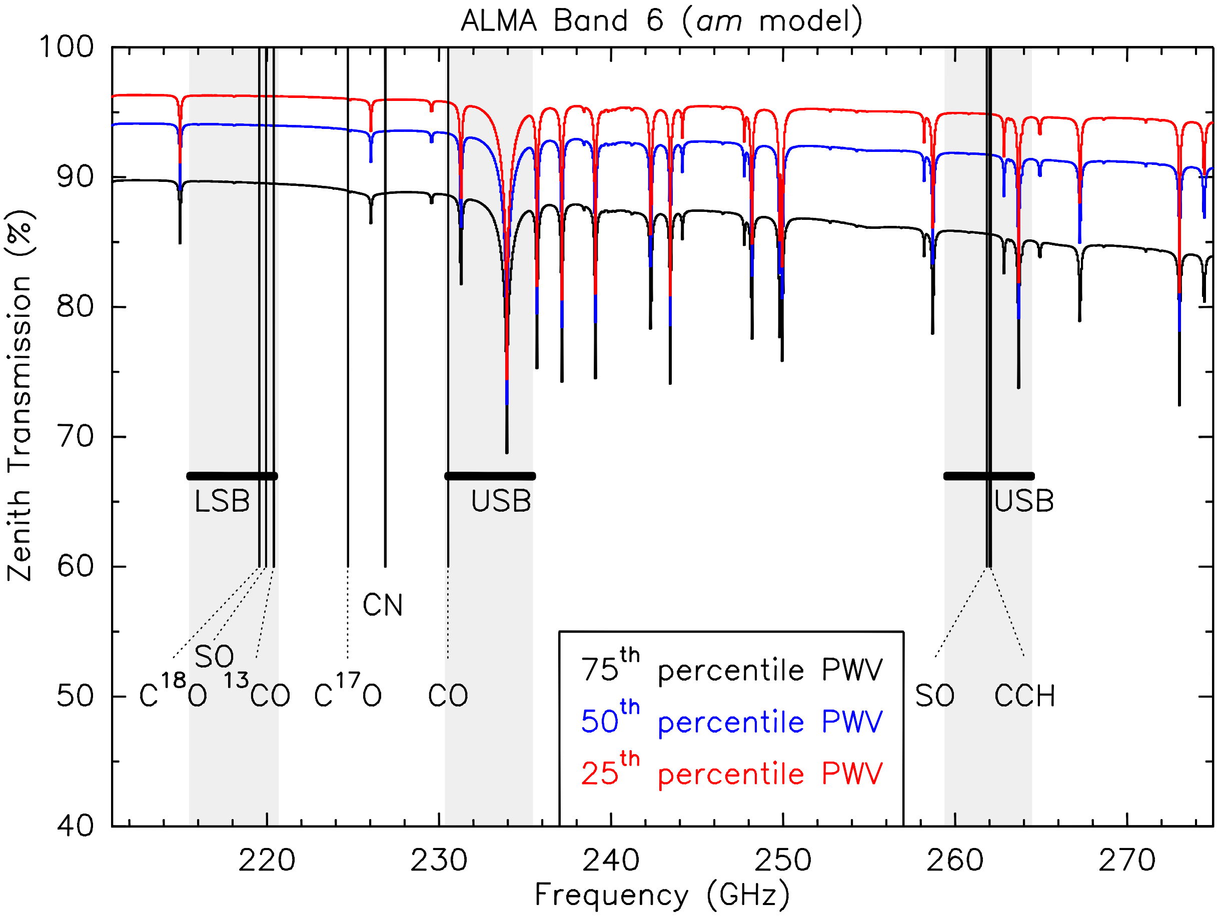

Fig. 1.— Atmospheric transmission model for ALMA over the Band 6 RF tuning range showing the relevant spectral lines for polarization observations. The two leftmost thick horizontal lines and shaded regions indicate a specific tuning (LO = 225.47 GHz) that would simultaneously observe the ^{12}CO/^{13}CO/C^{18}O (2-1) transitions, assuming an IF range of 5.0-10.0 GHz. The rightmost shaded region indicates the next most important frequency subband, which can only be observed in upper sideband. The atmospheric model is from the open source software "am" (Paine 2009).

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Table 2: Transitions in Band 6 suitable for Zeeman splitting studies

Species & Transition	Frequency (GHz)	Log(Intensity)	$2\delta\nu/B$ (Hz/μGauss)
SO 6, 5 → 5, 4	219.9499	-2.32	0.5^{a}
CN 2, 5/2, 5/2 → 1, 3/2, 3/2	226.87419	-2.67	0.7^{a}
CN 2, 5/2, 7/2 → 1, 3/2, 5/2	226.87478	-2.48	0.4^{a}
CN 2, 5/2, 3/2 → 1, 3/2, 1/2	226.87589	-2.90	1.2^{a}
CN 2, 5/2, 3/2 → 1, 3/2, 3/2	226.88742	-3.40	
CN 2, 5/2, 5/2 → 1, 3/2, 5/2	226.89212	-3.40	
SO 7, 6 → 6, 5	261.8437	-2.12	$\sim 0.5^{\mathrm{b}}$
CCH 3, 7/2, 4 → 2, 5/2, 3	262.0042	-2.73	0.35^{c}
CCH 3, 7/2, 3 → 2, 5/2, 2	262.0064	-2.86	0.49^{c}
CCH 3, 5/2, 4 → 2, 3/2, 3	262.0648	-2.88	0.49^{c}
CCH 3, 5/2, 2 → 2, 3/2, 3	262.0673	-3.06	0.70^{c}
CCH 3, 5/2, 2 → 2, 3/2, 2	262.0788	-3.94	0.89^{c}

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[a] Bel & Leroy (1989)

[b] Shinnaga & Yamamoto (2000)

[c] Bel & Leroy (1998)