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Science Requirements and Specifications for ALMA Band 7 Quarter Wave Plates

SCID-90.00.00.00-020-A-REP

Version: B

Status: Draft

2010-02-07

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0. Abstract

Knowledge of interstellar magnetic fields requires accurate measurements of continuum and spectral line polarization in the millimeter/submillimeter wavelength range. One of the most important ALMA bands for this research is Band 7. In 2007, it was decided by someone to remove the requirement for a Band 7 quarter wave plate (QWP) from the front end technical specifications. Fortunately, each amplitude calibration device (ACD) will be built with the mechanical and electrical provision to install a QWP at a later date. In this report, we reiterate the scientific motivation for sensitive polarization measurements in Band 7 which call for a QWP, and we outline the desired requirements for this device. The requirements are stricter than the original specifications in three ways: lower total loss (reflective and absorptive), lower induced cross polarization, and wider bandwidth.

1. Scientific Motivation

1.1. Background

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 via the Chandrasekhar-Fermi technique (Chandrasekhar & Fermi 1953) 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. The QWP will be most important for experiments aimed at detecting linearly-polarized emission, because they will effectively convert the ALMA linearly-polarized feeds into circularly-polarized feeds. 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 the QWP performance, the best spectral lines for polarization measurements in Band 7 must first be identified.

1.2. Important spectral lines

The most important spectral line known to exhibit detectable linear spectral polarization is ^{12}CO. 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). However, spectral line polarization is maximized for transitions with optical depth $\tau = 1$ (Deguchi & Watson 1984; Goldreich & Kylafis 1981). It is therefore likely that for deeply embedded regions isotopologues of CO will need to be observed. In order of decreasing abundance the frequencies are: ^{12}CO(3-2) 345.795 GHz; ^{13}CO(3-2) 330.588 GHz; C^{18}O(3-2) 329.331 GHz; C^{17}O(3-2) 337.061 GHz. Thus, for CO line polarization observations, we need quarter-wave plates that maintain excellent sensitivity at least across this range of frequencies. Figure 1 shows a Band 7 tuning that allows one to observe ^{12}CO, ^{13}CO and an SO line simultaneously (LO = 338.2 GHz).

Regarding the Zeeman effect, there are relatively few molecules that are both sufficiently abundant and paramagnetic. For example, the abundant CO molecule is in the common $^1\Sigma$ electronic state, and thus does not exhibit any appreciable Zeeman effect (e.g. Townes & Schawlow 1955). 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, within Band 7 there are a number of other diatomic molecules whose transitions tend to have strong emission and high Zeeman coefficients, and thus can be used to observe line linear polarization. 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; Padovani et al. 2009), and have high Zeeman coefficients: up to 2 Hz μG^{-1} (see Bel & Leroy 1989; Bel & Leroy 1998). These other molecules include CN ($\sim$ 340.2 GHz), SO (340.7, 344.3, and 346.5 GHz), and CCH (349 GHz). CN is of particular interest given its hyperfine structure (providing the ability to measure optical depth) and the fact that it also has a strong Zeeman coefficient. Similarly, 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. The frequencies of transitions with strong Zeeman coefficients and their expected intensities are given in Table 1. Figure 1 shows that CN, CCH, and SO can be observed simultaneously with an LO setting of 344.8 GHz.

In addition to the need for good sensitivity in the frequency range between C^{18}O and ^{12}CO for spectral line linear polarization, sensitive continuum linear polarization measurements are needed over both sidebands, i.e. the frequency range that should be specified must be at least 16 GHz at the very minimum. In order to take advantage of the region of the band with the very best atmospheric transmission, while straddling the strong Ozone lines near $\sim$ 332.8 and $\sim$ 343.2 GHz, one would like to be able to setup a continuum polarization observation from 335 to 339 GHz (LSB) and 347 to 351 GHz (USB).

2. Requirements for the QWP

Here we review the existing science requirements on polarization and the current specifications for the Band 7 QWP. We outline the deficiencies with the current specification and suggest revised specifications.

2.1. General Science Requirements for Polarization

From ALMA-90.00.00.00-001-A-SPE (released on 2006-07-28), we have:

- 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. A footnote to this requirement states: Meeting the polarization requirements is particularly important for band 7 and could require a quarter-wave plate.
- 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

Table 1: Transitions in Band 7 suitable for Zeeman splitting studies

Species & Transition	Frequency (GHz)	Log(Intensity)	$2\Delta\nu/B$ (Hz/μGauss)
CN 3, 5/2, 5/2 → 2, 3/2, 5/2	340.0081	-3.06	$\sim 0.2 - 2^{\mathrm{a}}$
CN 3, 5/2, 3/2 → 2, 3/2, 3/2	340.0196	-3.06	
CN 3, 5/2, 7/2 → 2, 3/2, 5/2	340.0315	-2.14	
CN 3, 5/2, 3/2 → 2, 3/2, 1/2	340.0354	-2.57	
CN 3, 5/2, 5/2 → 2, 3/2, 3/2	340.0354	-2.34	
CN 3, 7/2, 7/2 → 2, 5/2, 5/2	340.2478	-2.15	
CN 3, 7/2, 9/2 → 2, 5/2, 7/2	340.2478	-2.02	
CN 3, 7/2, 5/2 → 2, 5/2, 3/2	340.2485	-2.29	
CN 3, 7/2, 5/2 → 2, 5/2, 5/2	340.2618	-3.20	
CN 3, 7/2, 7/2 → 2, 5/2, 7/2	340.2649	-3.20	
SO 7(8) → 6(7)	340.7142	-1.94	$\sim 0.3^{\mathrm{b}}$
SO 8(8) → 7(7)	344.3106	-1.88	
SO 9(8) → 8(7)	346.5285	-1.80	
CCH 4, 9/2, 4 → 3, 5/2, 3	349.1085	-6.01	2.7^{c}
CCH 4, 9/2, 4 → 3, 7/2, 4	349.3128	-4.29	0.69^{c}
CCH 4, 9/2, 5 → 3, 7/2, 4	349.3377	-2.56	0.28^{c}
CCH 4, 9/2, 4 → 3, 7/2, 3	349.3390	-2.66	0.36^{c}
CCH 4, 7/2, 4 → 3, 5/2, 3	349.3993	-2.67	0.36^{c}
CCH 4, 7/2, 3 → 3, 5/2, 2	349.4007	-2.80	0.47^{c}
CCH 4, 7/2, 3 → 3, 5/2, 3	349.4146	-4.03	0.68^{c}
CCH 4, 7/2, 4 → 3, 7/2, 4	349.6036	-4.05	0.078^{c}
CCH 4, 7/2, 3 → 3, 7/2, 4	349.6190	-5.65	2.8^{c}
CCH 4, 7/2, 4 → 3, 7/2, 4	349.6298	-5.23	2.7^{c}
CCH 4, 7/2, 3 → 3, 7/2, 4	349.6451	-3.94	0.10^{c}

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[a] Exact values for CN are only available in the literature for lower frequency transitions (Bel & Leroy 1989), but do not vary much with increasing J, and can be calculated from Gordy & Cook (1984).

[b] Shinnaga & Yamamoto (2000)

[c] Bel & Leroy (1998)

which calibration of instrumental polarization can be performed. This applies to all receiver systems.

- Finally, there is a general requirement which is also pertinent to this discussion: "ALMA shall maximize sensitivity over its frequency bands."

2.2. Current Band 7 Front-End QWP Specifications

From the original front end requirements on the quarter wave plate, we have:

4.3.4 Quarter-Wave-Plate [FEND-40.00.00.00-00280-00 / T]:

A quarter wave plate that can be inserted into the beam of band 7 shall be provided. The center frequency of the quarter wave plate shall be 345 GHz. The combined absorptive and reflective losses shall be less than 0.5 dB. The induced cross-polar component shall be less than 10%. These specifications shall apply over the frequency range from 340 to 350 GHz.

2.3. Problems with the current QWP specification

- The band 7 (345 GHz) receivers have 4 GHz wide sidebands with centers separated by 12 GHz. The current specification does not provide sensitivity over both sidebands.

- A combined absorptive and reflective loss of 0.5 dB is equivalent to a 12% loss. This is equivalent to a loss of 6 antennas (assuming 50 antenna array) and violates the ALMA "sensitivity goal" that 95% of antennas shall be operational at any given time.

- In addition to the loss in signal, absorptive and reflective losses can cause significant changes in the apparent Tsys that are difficult to predict (but could be measured). For example, for an ambient cabin temperature of 300 K, a 12% absorptive loss could mean a Tsys increase of as much as 36 K (compared to the expected 100 K Tsys)!

- The quarter wave plates (single quartz plates) for the Submillimeter Array have less than ±3% cross-polar leakage over 14 GHz bandwidth (Marrone & Rao 2005). Also, there are a several new studies available that suggest very wide bandwidth multi-element wave plates are possible (Lilie 2001; Masson & Gallot 2006). From these results it is clear that wider bandwidth (than the current 10 GHz spec) quarter-wave plates are feasible. See the discussion on a possible ALMA Band 7 quarter wave plate design with 5 quartz layers that yields less than 2% leakage (electric field) across all of Band 7 by Marrone (2008).

3. Proposed Band 7 Front-End QWP Specs

In order to be in compliance with the scientific requirements for ALMA, the QWP specification should be:

4.3.4 Quarter-Wave-Plate [FEND-40.00.00.00-00280-00 / T]

A quarter wave plate that can be inserted into the beam of band 7 shall be provided. The centre frequency of the quarter wave plate shall be 340 GHz. The combined absorptive and reflective losses shall be less than 0.25 dB. The induced cross-polar component shall be less than 3%. These specifications shall apply over the frequency range from 329 to 351 GHz. It shall be possible to use the amplitude calibration device simultaneously with the quarter wave plate.

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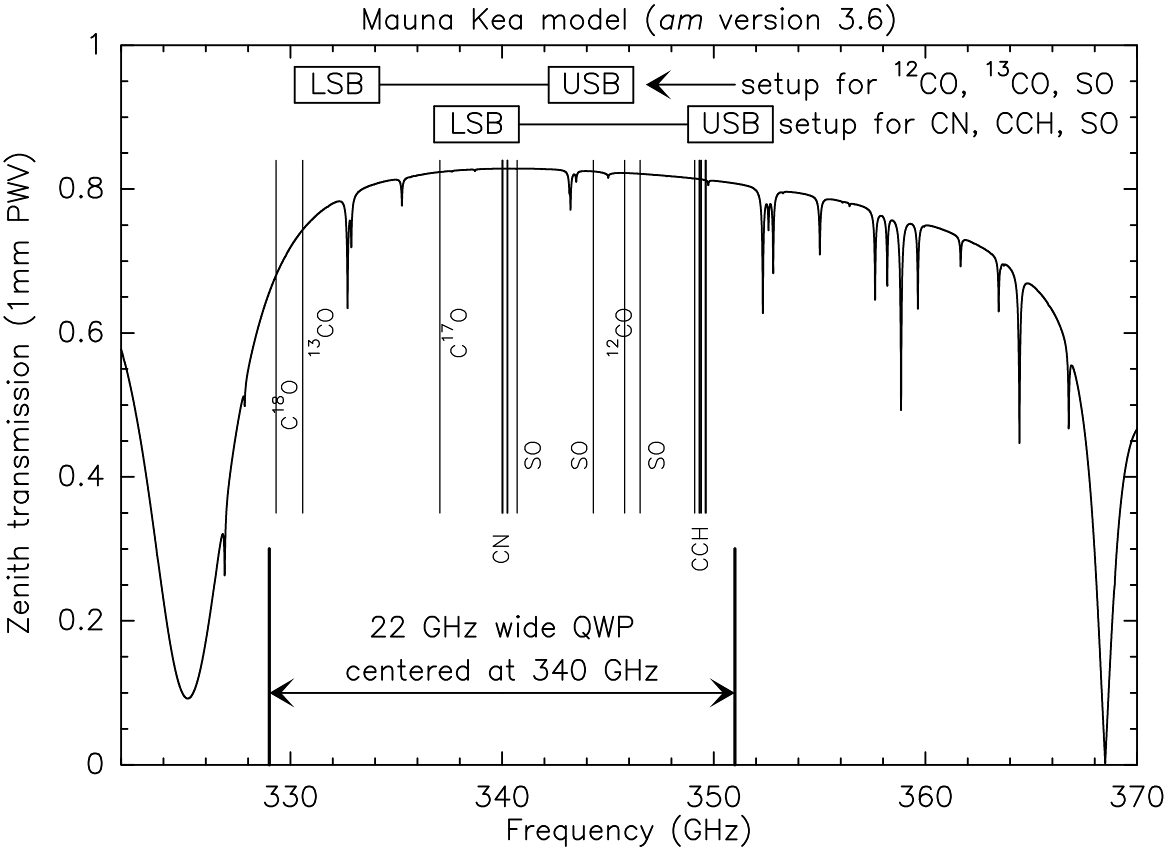

Fig. 1.— Atmospheric transmission model for Mauna Kea showing the relevant spectral lines for polarization studies in Band 7. Two potential tunings are shown: one capturing ^{12}CO and ^{13}CO simultaneously, and one capturing CN and CCH simultaneously. The frequency range of the proposed 22 GHz wide QWP centered at 340 GHz is also shown. The atmospheric model is from the open source software "am" (Paine 2009).

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