On the Accuracy of the ALMA Flux Calibration in the Time Domain and across Spectral Windows

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Abstract

A diverse array of science goals requires accurate flux calibration of observations with the Atacama Large Millimeter/submillimeter array (ALMA); however, this goal remains challenging due to the stochastic time-variability of the “grid” quasars ALMA uses for calibration. In this work, we use 343.5 GHz (Band 7) ALMA Atacama Compact Array observations of four bright and stable young stellar objects over seven epochs to independently assess the accuracy of the ALMA flux calibration and to refine the relative calibration across epochs. The use of these four extra calibrators allows us to achieve an unprecedented relative ALMA calibration accuracy of ~3%. On the other hand, when the observatory calibrator catalog is not up to date, the Band 7 data calibrated by the ALMA pipeline may have a flux calibration poorer than the nominal 10%, which can be exacerbated by weather-related phase degradation when self-calibration of the science target is either not possible or not attempted. We also uncover a relative flux calibration uncertainty between spectral windows of 0.8%, implying that measuring spectral indices within a single ALMA band is likely highly uncertain. We thus recommend various methods for science goals requiring high flux accuracy and robust calibration, in particular, the observation of additional calibrators combined with a relative calibration strategy, and observation of solar system objects for high absolute accuracy.

Unified Astronomy Thesaurus concepts: Flux calibration (544); Young stellar objects (1834); Protostars (1302); Stellar accretion (1578); Accretion (14); Interferometry (808)

1. Introduction

The accurate flux calibration of Atacama Large Millimeter/submillimeter Array (ALMA) observations is crucial to a wide variety of science goals. For example, comparison of fluxes at different wavelengths, often using observations obtained at different times, leads to a spectral index that probes grain growth in disks (e.g., Pinilla et al. 2019; Ueda et al. 2020) and galaxies (e.g., Williams et al. 2019; Sadaghiani et al. 2020). In some cases, these spectral indices are measured within a band (Lee et al. 2020; Pérez et al. 2020), which minimizes time-variability in the flux calibration but may introduce other uncertainties. The flux calibration also affects results from programs that require accurate monitoring with time (e.g. Cleeves et al. 2017; He et al. 2019), ratios of emission lines in different bands (e.g., Matrà et al. 2017; Flaherty et al. 2018), or comparison of fluxes from different objects in a survey (e.g Ansdell et al. 2016; Tobin et al. 2020). For deep ALMA observations, multiple independently calibrated execution blocks are typically concatenated prior to imaging; accurate relative calibration improves the resulting image quality and self-calibration solutions (Andrews et al. 2018).

Obtaining an accurate ALMA flux calibration, however, is exceptionally challenging due to the paucity of bright and stable calibrator sources in the submillimeter/millimeter sky. The most reliable calibrators are solar system objects, with large and predictable millimeter fluxes that are known to ~5% (Butler 2012); unfortunately, solar system calibrators are located only in the plane of the ecliptic, and are therefore often not visible at the time of observation or are widely separated on the sky from the science target. As a result, ALMA observations are typically calibrated using “grid” calibrators—a collection of ~40 mm bright quasars distributed homogeneously across the sky (Remijan et al. 1919). Quasars, however, are variable in both flux and spectral index, so the grid calibrator fluxes must be determined by observation of a solar system calibrator every 10–14 days in multiple ALMA bands (Remijan et al. 1919). The grid calibrators are typically observed in both sidebands of Band 3 (91.5 and 103.5 GHz) and Band 7 (343.5 GHz), with Band 6 (233 GHz) occasionally used in place of Band 7 when weather conditions are poorer. The procedure for ALMA flux calibration is thus as follows: a recently monitored grid source is first observed (van Kempen et al. 2014), and its flux density in each spectral window is calculated by extrapolating from the nearest-in-time Band 3 measurement using a power-law spectral index fit to the nearest-in-time pair of Band 3 and 7 measurements taken within 3 days of each other. This flux scale is then transferred to the phase calibrator—typically a fainter quasar close to the science target—and in turn to observations of the science target taken between phase calibrator scans.

Despite the need for good flux calibration, there are few examples in the literature where the ALMA flux calibration accuracy is independently assessed. The time-variability of the ALMA grid calibrators has been quantified by the ALMACAL project for investigating quasar physics (Bonato et al. 2018). The grid calibrators have been modeled using continuous time stochastic processes by Guzmán et al. (2019), which can provide flux interpolation, forecasting, and uncertainty estimates taking into account the inherent time-variability.
Two ALMA projects (PI: Logan Francis, project IDs 2018.1.00917.S, 2019.1.00475.S) are currently underway to precisely measure the submillimeter variability of three deeply embedded protostars in the Serpens Main molecular cloud at disk and inner envelope (<2000 au) scales. In this work, we take advantage of the relative flux calibration strategy of these projects to independently test the accuracy of the flux scale determined during ALMA pipeline processing from the available grid calibrator data. The remainder of this paper is structured as follows: In Section 2, we describe the ALMA observations of our targets and data reduction, while in Section 3 we present our relative calibration technique and analyze the pipeline calibration accuracy. In Section 4, we discuss the impact of our findings on various science goals requiring good flux calibration accuracy and offer suggestions for best practices in reducing ALMA data. Section 5 briefly summarizes the results of this work.

2. Observations

Our ALMA programs (2018.1.00917.S, 2019.1.00475.S) observe three potentially varying protostars (SMM 1, EC 53, and SMM 10; Yoo et al. 2017; Johnstone et al. 2018; Contreras Peña et al. 2020) and five additional young stellar object (YSO) calibrators (SMM 2 SMM 9, SMM 4, SMM 3, and SMM 11) in the Serpens Main molecular cloud (distance: 436.0 ± 9.2 pc; Ortiz-León et al. 2017) at 343.5 GHz. These targets were selected based on their variability or stability as determined by the James Clerk Maxwell Telescope (JCMT) Transient Survey (Herczeg et al. 2017). The ongoing Transient Survey monitors the brightness of YSOs in eight star-forming regions at 450 μm and 850 μm (352.9 GHz) at a monthly or better cadence in order to identify changes in envelope brightness resulting from protostellar accretion variability. The JCMT resolution in Serpens Main is ~6100 au, however, and the bulk of the envelope response likely occurs at smaller scales (Johnstone et al. 2013). Our contemporaneous higher-resolution (~1750 au) ALMA observations thus provide a useful measurement of how protostellar envelopes respond to accretion variations. The brightness of all our YSO calibrators at the JCMT has remained stable over the first 4 yr of the Transient Survey to <3%. Since accretion outbursts of the YSO calibrators are possible, observing multiple calibrators provides redundancy in the unlikely event that one becomes variable.

All observations are taken with the stand-alone mode of the Morita Array, otherwise known as the Atacama Compact Array (ACA), a subarray of ALMA consisting of 12 closely-spaced 7 m diameter antennas. The ACA correlator is configured in time division mode with the default Band 7 continuum settings to provide four low-resolution spectral windows with 1.875 GHz of bandwidth across 128 channels, for a total bandwidth of 7.5 GHz. We have obtained seven epochs of observations of our targets as of 2020 July with a typical resolution of 4″ (~1750 au) and rms noise of ~1 mJy. Names and coordinates of our targets are provided in Table 1, while the dates of observation and the flux and amplitude calibrators selected by the ALMA online system for our seven epochs are listed in Table 2. Deconvolved images of our targets and calibrators constructed from concatenation of all available continuum data with the relative calibration discussed in Section 3 applied are shown in Figure 1. While SMM 2 is bright and stable in the JCMT Transient Survey, at the ACA resolution it is too faint and extended to obtain a useful calibration. We thus use SMM 9, SMM 4, SMM 3, and SMM 11 for relative calibration and hereafter refer to them as CAL 1–4. Our target fluxes are >300 mJy (except SMM 2), and as a result we can achieve a formal signal-to-noise ratio (S/N) > 300; however, our images are dynamic range limited to an S/N of ∼100. We apply phase-only self-calibration to our observations, the procedure for and effects of which are discussed in Section 3.3. To avoid errors introduced by the deconvolution process in comparing target fluxes between observations, we perform our analysis in the u-v-plane, where careful error analysis is more tractable.

3. Relative Calibration of Atacama Compact Array data

Our four YSO calibrators are monitored to allow the precise measurement of relative changes in the submillimeter flux of our science targets. Since JCMT monitoring has established that the brightness of the YSO calibrators is stable over 4 yr to a level of ~3%–5% (Mairs et al. 2017), we can measure a relative calibration offset between epochs, providing a direct test of the ALMA calibration accuracy. Here we describe our relative calibration method, examine how the ALMA flux accuracy depends on the catalog, and quantify the accuracy of the ALMA flux calibration between spectral windows.

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**Table 1**

| Name          | ALMA Name       | Other Millimeter Source Names | ACA Field Center (ICRS) |
|---------------|-----------------|------------------------------|-------------------------|
| Serpens SMM 1 | Serpens_Main_850_00 | Ser-emb 6, FIRS1            | 18:29:49.79 + 01:15:20.4 |
| EC 53         | Serpens_Main_850_02 | Ser-emb 21                 | 18:29:51.18 + 01:16:40.4 |
| Serpens SMM 10 IR | Serpens_Main_850_03 | Ser-emb 12                 | 18:29:52.00 + 01:15:50.0 |
| Serpens SMM 2 | Serpens_Main_850_10 | Ser-emb 4 (N)              | 18:30:00.30 + 01:12:59.4 |
| Serpens SMM 9 (CAL 1) | Serpens_Main_850_01 | Ser-emb 8, SH2-68N         | 18:29:48.07 + 01:16:43.7 |
| Serpens SMM 4 (CAL 2) | Serpens_Main_850_08 | ...                       | 18:29:56.72 + 01:13:15.6 |
| Serpens SMM 3 (CAL 3) | Serpens_Main_850_09 | ...                       | 18:29:59.32 + 01:14:00.5 |
| Serpens SMM 11 (CAL 4) | Serpens_Main_850_11 | ...                       | 18:30:00.38 + 01:11:44.6 |

**Table 2**

| Epoch | Date       | Flux Calibrator | Phase Calibrator |
|-------|------------|-----------------|------------------|
| 1     | 14-Oct-2018| J1924-2914      | J1851 + 0035     |
| 2     | 06-Mar-2019| J1751 + 0939    | J1743-0350       |
| 3     | 07-Apr-2019| J1517-2422      | J1751 + 0939     |
| 4     | 15-May-2019| J1924-2914      | J1743-0350       |
| 5     | 04-Aug-2019| J1924-2914      | J1743-0350       |
| 6     | 20-Sept-2019| J1924-2914 | J1851 + 0035     |
| 7     | 29-Oct-2019| J1924-2914      | J1851 + 0035     |
That used for the JCMT Transient Survey (Mairs et al. 2017) and its application to interferometric data in Francis et al. (2019). The “mean correction factor” (MCF) for epoch \( i \) and calibrator \( j \) is thus

\[
\text{MCF}_{ij} = \frac{\sum_{l=1}^{7} F_{ij}^l}{7},
\]

while the uncertainty in the MCF is

\[
\sigma_{\text{MCF}_{ij}} = \sqrt{\frac{1}{NF_{ij}} \left( \sum_{l=1}^{7} F_{ij}^l \sigma_{F_{ij}^l}^2 + \sum_{l=1}^{7} \sigma_{F_{ij}^l}^2 \right) \frac{1}{N}}.
\]

To determine a relative flux calibration factor (rFCF) for each epoch from our YSO calibrators, we take the average of the four MCFs for calibrators in that epoch, such that

\[
r\text{FCF}_i = \frac{1}{4} \sum_{j=1}^{4} \text{MCF}_{ij}.
\]

The MCFs and rFCFs thus calculated are listed in Table 3, and plotted versus the observing date in the top panel of Figure 2. For any epoch, the MCFs have a range <7% and standard deviation <3%. The relative calibration accuracy is thus 3% or better, which is unprecedented for ALMA data. We find the YSO rFCFs have a
standard deviation of 14% and range of 45%, in contrast with the expected nominal Band 7 flux calibration accuracy of 10% (Braatz 2020). Notably, the second epoch requires a much larger rFCF, of ~30%.

3.2. Grid Calibrator Flux Updates

Because it represents a systematic offset in flux density, the large rFCF required in epoch 2 may result from a poor time interpolation if the grid calibrator catalog was out of date at the time of the original reduction. We thus queried the flux of each grid calibrator in 2020 April and compared its flux and spectral index with the values used by the pipeline in Table 4. Epochs 2 (2019 March 6) and 6 (2019 September 20) have changed by ~20%, while smaller changes to epochs 3 and 4 of a few percent have also occurred. This large change in catalog flux is likely due to the inclusion of additional grid calibrator fluxes in the ALMA catalog since the dates of the original reductions.

With the updated pipeline values for the grid calibrator fluxes, we rescale the pipeline-calibrated visibilities and compute the MCFs and rFCFs again (middle panel of Figure 2). The magnitude of the rFCF in epoch 2 is now ~15%, while the rFCFs overall now have a standard deviation of 9% and range of 26%, consistent with the nominal flux calibration accuracy. The reduced range of the rFCFs demonstrates the importance of using the most up-to-date catalog for achieving a good flux calibration. Further discussion and suggestions for best practices are given in Section 4, while typical delays between observation of the flux calibrators and ingestion into the catalog are provided in Appendix D.

3.3. Effect of Self-calibration

Weather conditions and instrumental effects can result in noisy or incorrect visibility phases, the extent of which can vary between observing epochs. Noisy phases may result in decorrelation and loss of flux during an observing scan (Brogan et al. 2018), which would bias our MCFs to higher values. We thus apply self-calibration to our YSO calibrators to assess its effect on our relative calibration.

Three rounds of phase-only self-calibration were performed using solution intervals of a scan length, 20.2 s, and 5.05 s (an ACA integration is 1.01 s in time division mode). Models of each source were constructed with the casa tclean task with a robust weighting of 0.5, and calibration solutions were allowed to vary between spectral windows. Repeating our uv-plane point-source fits, we find the calibrator fluxes to increase by a few percent for all but epoch 2, where the improvement was ~15%. The resulting MCFs and rFCFs are shown in the bottom panel of Figure 2; we exclude the MCF of CAL 1 in epoch 2 from the calculation of the rFCF as it as an outlier in its flux increase. We find the overall MCF standard deviation remains at ~3%, while the standard deviation and range of the rFCFs are now further reduced to 5% and 17%, respectively; this is largely the result of the ~15% in flux of the YSO calibrators in epoch 2, which pulls the rFCFs for the other epochs closer to 1. Phase self-calibration is thus important for relative calibration in order to avoid biasing of the flux rescaling.

3.4. Calibration across Spectral Windows

We repeat the process of obtaining our MCFs for each spectral window independently using the updated grid calibrator fluxes
and phase self-calibrated data, thus allowing us to measure the accuracy of the ALMA flux calibration between spectral windows. As our YSO calibrator sources have an S/N > 300 using data from all four spectral windows, the factor of 2 decrease in S/N resulting from use of a single window should not significantly affect our analysis.

In Figure 3, we show the MCF for each YSO calibrator and spectral window normalized to the MCF obtained using data from all spectral windows, where the error bars are computed using Equation (2) with normalization treated as a constant. The magnitude of the normalized MCFs is small but correlated across calibrators, implying an additional source of uncertainty in the relative flux calibration between spectral windows. We note that we obtain similar results before and after the self-calibration of our data in Section 3.3.

Flux calibration errors between spectral windows may be systematic if there is a frequency dependence, which could potentially occur if the pipeline-generated spectral index of the grid calibrator was incorrect. We thus fit a power law of the form $C_{\nu}^{\alpha}$ to the normalized MCFs versus frequency using the function `optimize.curve_fit` in the `scipy` python package and assuming that the uncertainty in the normalized MCFs is entirely

### Table 4

| Epoch | Pipeline Run Date | Flux Density (Jy) | Spectral Index | Flux Density Change (%) |
|-------|------------------|------------------|----------------|-------------------------|
|       |                  | Original | Updated       | Original | Updated       |                          |
| 1     | 17-Oct-2018      | 2.65 ± 0.21   | 2.65 ± 0.09   | −0.609 ± 0.019 | −0.609 ± 0.019 | 0.0                      |
| 2     | 18-Apr-2019      | 2.08 ± 0.14   | 2.44 ± 0.07   | −0.590 ± 0.037 | −0.482 ± 0.014 | 17.3 ± 8.6               |
| 3     | 18-Apr-2019      | 2.14 ± 0.13   | 2.22 ± 0.07   | −0.335 ± 0.025 | −0.306 ± 0.021 | 3.7 ± 7.1                |
| 4     | 22-Sep-2019      | 2.13          | 2.17 ± 0.06   | ...          | −0.638 ± 0.044 | 1.8                      |
| 5     | 06-Sep-2019      | 2.15 ± 0.04   | 2.15 ± 0.04   | −0.668 ± 0.038 | −0.668 ± 0.038 | 0.0                      |
| 6     | 30-Sep-2019      | 2.40 ± 0.10   | 2.88 ± 0.06   | −0.642 ± 0.028 | −0.495 ± 0.039 | 20.0 ± 5.6               |
| 7     | 19-Nov-2019      | 3.16 ± 0.06   | 3.16 ± 0.06   | −0.453 ± 0.008 | −0.453 ± 0.008 | 0.0                      |

Note. All Fluxes are evaluated at center frequency of first spw of 336.495 GHz. The original grid calibrator flux uncertainty and spectral index were not recorded by the pipeline in epoch 4.
due to the point-source fitting, and find that all but epoch 2 have a power-law index consistent with zero.\footnote{We have also performed the fits using a residual bootstrapping procedure incorporating Monte Carlo treatment of the noise, which can provide more robust error estimates for small data sets. We find the bootstrapping slopes and uncertainties are similar to those from optimize.curve_fit, except for epoch 0, where the error bars are much larger ($\alpha = -0.2^{+0.2}_{-0.9}$).} Thus, in only one epoch there is evidence of a residual frequency dependence in the flux calibration. Checking for variability in the pipeline spectral index near the date of epoch 2, we find that the original and updated spectral indices of J1751 + 0939 are $-0.590 \pm 0.037$ and $-0.482 \pm 0.014$, both of which are reasonably consistent with historical measurements (see Appendix B). If we correct the epoch 2 updated spectral index of J1751 + 0939 using the value of the normalized MCFs, the true spectral index would be $\sim 0$. This value is extremely inconsistent with monitoring of J1751 + 0939, and moreover, such an index is unlikely for a quasar, as the quasar brightness at millimeter wavelengths is dominated by synchrotron emission (Planck Collaboration et al. 2011; van Kempen et al. 2014). A large systematic error introduced by an incorrect quasar spectral index is therefore ruled out for epoch 2.

We now consider if variation in the normalized MCFs is due to random or to systematic errors introduced from the point-source or relative flux calibration of spectral windows, which also could explain epochs where there is a relative offset between all spectral windows and no significant systematic frequency dependence (e.g., epochs 3 and 4). The left panel of Figure 4 shows the histogram of the normalized MCFs, which is well described by a Gaussian fit with $\sigma = 0.9\%$. We assume the width of this distribution can be described as the sum of two uncorrelated random errors: those introduced from the point-source fits in the calculation of the normalized MCFs and those from a relative calibration error between spectral windows; systematic frequency-dependent contributions are assumed to be negligible. In the center panel of Figure 4, the blue histogram shows the scatter in the normalized MCFs where the mean across the four calibrators per spectral window and epoch (the black bars in Figure 3) has been subtracted, i.e.,

$$\left(\frac{\text{MCF}_{i,j,k} - \frac{1}{4} \sum_{j=1}^{4} \text{MCF}_{i,j,k}}{\text{MCF}_{i,j}}\right).$$

where $k$ is the spectral window. A Gaussian fit to the blue histogram has a width of $\sigma = 0.5\%$, which is approximately the same as the typical uncertainty in our point-source flux measurements for a single spectral window. In the right panel of Figure 4, the red histogram shows the distribution of the subtracted mean values, i.e.,

$$\frac{\sum_{j=1}^{4} \text{MCF}_{i,j,k}}{\text{MCF}_{i,j}}.$$

A Gaussian fit to the red histogram has a width of $\sigma = 0.8\%$, which we identify as the magnitude of the relative flux calibration error between spectral windows.

This additional source of uncertainty between spectral windows would imply that the significance of the spectral index in epoch 2 ($2\sigma$) is overestimated, and may simply be the result of outlier values in the relative calibration of spectral windows. We thus run a Monte Carlo simulation to generate sets of 16 normalized MCFs according to the sum of the random errors from the flux measurement and relative calibration between spectral windows. We then measure the power-law index $\alpha$ for each simulated set of normalized MCFs and repeat this process 10,000 times. The resulting distribution of $\alpha$ has a standard deviation of $\sigma = 0.3$ and is shown in Figure 5. The probability of obtaining $\alpha \geq 0.4$ from random errors is $\sim 2.2\%$ for one observation or $\sim 16\%$ for seven, and thus the slope in epoch 2 is plausibly explained as the result of a relative calibration error of $\sim 0.8\%$ between spectral windows. This relative error implies an additional source of uncertainty when comparing source fluxes between spectral windows, the impact of which is discussed further in Section 4.2.

4. Discussion

The preceding analysis has shown that (1) without the most up-to-date calibrator catalog, the relative flux calibration accuracy of delivered ALMA data may be larger than the nominal 10\%, and (2) within a single ALMA execution block in one band, there exists a $\sim 0.8\%$ flux calibration uncertainty between spectral windows. We now discuss the impact of these two points on various science goals and how a typical ALMA user can address them, and provide some suggestions for obtaining optimal flux calibration accuracy.
The accuracy of the original pipeline flux calibration identified from the range of fRCF magnitudes is a particular concern for time domain science cases that require measurement of changes in source flux smaller than a factor of a few times the calibration accuracy. As an example, if we naively compared a single source between outlier epochs 2 and 7 before catalog updates or self-calibration, we would see a ~45% change in flux. Assuming that the Band 7 ALMA calibration accuracy is ~10%, as is stated in the ALMA documentation (Braatz 2020) and often assumed in the literature, we would mistakenly identify this as a robust detection of variability.

A ~0.8% flux calibration uncertainty between spectral windows strongly affects the accuracy of in-band spectral index measurements due to the short length of the frequency “lever arm.” A brief example of measuring a spectral index with various ALMA settings is illustrative. Consider observations of a source using the default ALMA spectral window frequencies for continuum observations in Bands 3 and 7, shown in Table 5. The absolute uncertainty of a spectral index measured between frequencies \( \nu_1 \) and \( \nu_2 \) is \( \sigma_{\alpha} = \sqrt{2} \sigma_F / \ln(\nu_2/\nu_1) \), where \( \sigma_F \) is the relative flux uncertainty and \( \nu_2 > \nu_1 \). Assuming \( \sigma_F = 0.8\% \), the uncertainty in the spectral index comparing spectral windows 1 and 4 is thus 0.08 for Band 3 and 0.28 for Band 7. For comparison, a spectral index measured between spectral window (spw) 1 in Band 3 and spw 4 in Band 7 with the nominal \( \sigma_F = 10\% \) would have an uncertainty of 0.01. These are only lower limits on the expected uncertainties, as in reality any flux measurement will have additional uncertainties from the model fitting. Even a small relative flux calibration error between spectral windows is therefore problematic for measurement of in-band spectral index at the higher ALMA frequencies.

In general, underestimating the flux calibration accuracy is a problem for science goals where this is the limiting factor in the analysis. A recent example is the modeling of millimeter-scattering processes in the TW Hya protoplanetary disk (Ueda et al. 2020). The authors fit radiative transfer models with and without scattering to spectral energy distributions of the object obtained in ALMA Bands 3, 4, 6, 7, and 9. Both models fit the data within the uncertainty of the flux measurements, which were dominated by the flux calibration accuracy. While Ueda et al. (2020) carefully checked the variability of their calibrators and consequently adopted larger than nominal uncertainties, typical publications containing ALMA data assume the nominal uncertainties in their interpretation. Careful analysis is recommended for any case where the significance of the results strongly depends on the calibration accuracy.

4.2. Best Practices for ALMA Flux Calibration

We have found that an out-of-date calibrator catalog can increase the flux calibration uncertainty above the nominal ALMA values. For any ALMA observation, it is thus worth ensuring that the catalog used by the pipeline is up to date. An ALMA user can compute the flux density of a grid calibrator using the same procedure as the pipeline with the function `getALMAFlux` in the `analysisutils` python package. If the flux computed with `getALMAFlux` differs from the pipeline value, additional measurements close to the date of observation have likely been added or updated. We find that the ALMA catalog should in general be stable after a month (see Appendix D), so an ALMA user requiring the most accurate absolute calibration should check for catalog changes a month after the science observation.

Changes to the flux calibrator values should also be checked for consistency with the calibrator light curves. In principle, the phase calibrator can also be used for a secondary consistency check; however, this is difficult as the phase calibrators are also variable quasars, and are monitored infrequently, and are often fainter (see Appendix C).

Users examining the pipeline weblog to check calibrator fluxes should be cautious of interpreting the derived quantities for calibrators presented in tabular form on the `hifa_gfluxscale` page as flux densities, because this is only true in the limit of high S/N. Although these quantities have units of Jy, they are merely scale factors from the calibration table, and will be biased upward in cases of low S/N and/or decorrelation. Nevertheless, when these factors are applied to the visibility data in the later stage `hif_applycal`, they will yield (except in extreme cases of low S/N) calibrated amplitudes that represent the correct flux density and will produce an image of a point source with the correct flux density.

Once the calibrator catalog has been updated, an ALMA user can rescale their visibility amplitudes using the `applycal` task in CASA. Alternatively, the values in the `flux.csv` file used in stage 1 of the pipeline can simply be modified and the pipeline rerun with that file present in the working directory.

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**Table 5**

| Band | spw 1 (GHz) | spw 2 (GHz) | LO1 (GHz) | spw 3 (GHz) | spw 3 (GHz) |
|------|-------------|-------------|-----------|-------------|-------------|
| 3    | 90.5        | 92.5        | 97.5      | 102.5       | 104.5       |
| 4    | 138.0       | 140.0       | 145.0     | 150.0       | 152.0       |
| 5    | 196.0       | 198.0       | 203.0     | 208.0       | 210.0       |
| 6    | 224.0       | 226.0       | 233.0     | 240.0       | 242.0       |
| 7    | 336.5       | 338.5       | 343.5     | 348.5       | 350.5       |

**Note.** LO1 is the local oscillator frequency.

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8 https://casaguides.nrao.edu/index.php?title=Analysis_Utillies; https://safe.nrao.edu/wiki/bin/view/Main/CasaExtensions
9 Available at https://almascience.eso.org/sc/
10 The next ALMA pipeline release (2020.1.0) will now also show the mean calibrated visibility amplitude in the `hifa_gfluxscale` weblog table, which is usually a very good match to flux density in the subsequent calibrator image.

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If better than the nominal ALMA flux calibration is desired, several strategies should be considered, depending on whether the relative scaling between observations or the absolute accuracy is of greater importance. For relative scaling of observations at the same frequency, a good model of one or more bright and stable science targets can be used to rescale the visibility amplitudes using ratios of the model flux between epochs. Phase self-calibration of the science targets is important to carry out in order to reduce the effect of varying phase noise on the flux scaling between epochs. For science goals where time-variability of the sources is of interest, additional stable objects should be added as “science” targets in Phase 1 of the ALMA Observing Tool as we have done for our ALMA Serpens protostar variability projects. This strategy allows us to reach a relative flux calibration accuracy of ~3% that, if reproduced for other projects, would enable science goals not possible with ALMA’s nominal flux calibration accuracy. The quasar CHECK sources automatically added to long-baseline ($\theta_{\text{beam}} < 0.75\text{mas}$) and high-frequency (>385 GHz) observations by the Observing Tool (used by the pipeline to assess astrometric accuracy and phase and amplitude transfer) are too faint to rely on for the purpose of rescaling observations, are not guaranteed to be the same object between executions, and are themselves variable. For observations of a time-variable spectral line against a constant continuum, an “in-band calibration” strategy requiring no extra calibrators has been successfully used for monitoring of the carbon star IRC +10216 (He et al. 2019), and a similar technique was used to show a robust change in the $\mathrm{H^3\text{C}^+}$ line flux of the IM Lup protoplanetary disk by Cleeves et al. (2017). Surveys observing the same field repeatedly at a given frequency will benefit from using relative calibration to rescale the visibilities of individual execution blocks, as this will reduce artifacts in deep images and improve the self-calibration solutions. A variant on this strategy was used by the DSHARP survey, wherein a model-free approach exploiting the inherent $uv$-plane symmetry of disk sources was adopted (Andrews et al. 2018).

For spectral scans, if the tunings are split between schedule blocks, they might be executed with different calibrators and might be executed weeks or months apart. For this reason, it is beneficial to include a short observation of a grid source near the science target as an additional science target in order to be sure that you have a common source with which to test the consistency of the flux calibration across executions and apply corrections to the calibrated data when necessary.

Relative calibration may be helpful for comparisons of archival ALMA data to search for time-variability. However, careful analysis is needed for identification of stable reference targets for relative calibration, and for mitigating the effects of differences in $uv$-coverage and observing frequency, which is important for both the reference and science targets (see Francis et al. 2019).

For observations where high absolute accuracy is needed, requesting a solar system object observation is best if one is available; however, this is not possible for high-frequency and/or long-baseline observations with small synthesized beams where the solar system objects are resolved out. For such observations, a grid calibrator should be included, and additional observations with the ACA of a solar system object and the desired grid calibrator as science targets should be requested within a few days of the primary observation and at the same frequency. For analysis of archival data, a user can search for observations within a few days of the observing date in the same ALMA band that include one of the science targets or calibrators as well as a solar system object.

5. Conclusions

We have used ALMA observations of four stable YSO calibrators to independently assess the accuracy of the ALMA pipeline flux calibration between observations and spectral windows. Our primary findings are as follows:

1. Without an up-to-date catalog including all flux calibrator observations near the observing date, the ALMA flux calibration accuracy in Band 7 may be poorer than the nominal 10%. This problem can be identified and corrected by an ALMA user using the analysisUtils python package.

2. ALMA’s relative flux calibration accuracy may be further worsened by phase decorrelation due to poor weather if self-calibration is not possible or not applied.

3. We obtain a relative ALMA flux calibration accuracy of ~3% with observations of four additional bright and stable YSO calibrators and simple $uv$-plane modeling. Calibration to this level of accuracy enables science goals that would not be possible within the nominal ALMA flux calibration uncertainties.

4. We find our observations show a relative flux calibration uncertainty between spectral windows of 0.8%, implying that measuring spectral indices within an ALMA band may be highly uncertain, e.g., with default Band 7 continuum spectral windows of bright targets, the spectral index uncertainty from in-band measurement is ~0.3.

5. In light of typical ALMA observing practices and constraints, science goals requiring high flux accuracy should be performed in a manner that assures a robust calibration, such as the observation of additional calibrators combined with a relative calibration strategy, and observation of solar system objects for high absolute accuracy.

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Software: astropy (Astropy Collaboration et al. 2013), matplotlib (Hunter 2007), Common Astronomy Software Application (CASA) 5.6.1 (McMullin et al. 2007).

Appendix A

ALMA Flux and Phase Calibrator Light Curves

In Figure 6, we show the catalog light curves of the grid flux calibrators and phase calibrators (see Table 2) used for our
observations centered around each observing epoch. The upper and lower sidebands of the Band 3 observations are recorded separately in the catalog as the frequency difference between sidebands is >10% of the typical observing frequency, and the calibrators are bright enough to have high S/N in both sidebands.

Figure 6. Catalog light curves of the grid flux calibrators (left column) and phase calibrators (right column) for our ACA observations, centered on the observing dates (dashed line). Band 3, 6, and 7 observations are shown as red, green, and blue markers, respectively. Flux measurements for Band 3 are made separately for the upper and lower sidebands. The light curves are shown with a 2 month range around the observing date for the flux calibrators and 4 months for the less frequently monitored phase calibrators.
Appendix B
Spectral Index of Epoch 2 Flux Calibrator

In Figure 7, we show catalog spectral index measurements for $J1751 + 0939$, the grid calibrator for epoch 2, with the date of our observations and the original and updated pipeline spectral index values overlaid.

Appendix C
Checking Consistency of the ALMA Flux and Phase Calibrator Flux Scales

In principle, if the phase calibrator used by ALMA has been recently observed, an rFCF can be computed using the ratio of the catalog flux to the pipeline flux of the phase calibrator. As

**Figure 7.** Catalog (purple circles), original pipeline (red triangle), and updated (green square) pipeline spectral index of the flux calibrator $J1751 + 0939$ used in epoch 2. The date of the second epoch of ACA observations is overlaid with a black dashed line. The right panel shows a zoom-in on the second epoch within an interval of 2 months.
the phase calibrators are also variable quasars and are typically less frequently monitored, these rFCFs are unlikely to be any better than the grid calibrator scaling, but a large value may suggest a poor flux calibration. On the other hand, it is not generally possible to use the phase calibrator to compute the normalized MCFs used to identify differences in scaling between spectral windows (Section 3.4), as the phase calibrators typically have lower S/N than our YSO calibrators.

In Figure 8, we compare the MCFs computed using our YSO calibrators and the updated pipeline flux calibration with the rFCFs calculated using the phase calibrator alone. In three of seven epochs, the phase calibrator rFCF agrees well with the YSO rFCF, but is inconsistent for the other four. In comparing with the light curves in Figure 6, there is no clear relationship of a shorter delay between observation of our YSO calibrator and the phase calibrators with having a correct rFCF, except in the case of epoch 3 where a grid source observed within a week was used as a phase calibrator.

Appendix D
ALMA Monitoring Cadence and Catalog Ingestion Delay

Using tools in analysisUtils, we find that the ALMA calibrator catalog entries made over the past several years typically have a delay between observation and ingestion into the catalog. The mean value is 2–3 days, with the 90th percentile value being ≈1 week and a maximum value of 2 months. In Table 6, we show the delays for the flux calibrators used for our ACA observations of variable protostars.

| Epochs                | Flux Calibrator | Median Lag (days) | 90th Percentile Lag (days) | Maximum Lag (days) |
|-----------------------|-----------------|-------------------|---------------------------|-------------------|
| 1, 4, 5, 6, 7         | J1924-2914      | 2.0               | 8.0                       | 86                |
| 2                     | J1751+0939      | 2.0               | 9.0                       | 64                |
| 3                     | J1517-2422      | 2.0               | 8.0                       | 168               |

Table 6
Flux Calibrator Catalog Ingestion Delay

Appendix E
Measurement Set Rescaling in CASA

Visibility amplitude in a CASA measurement set can be rescaled using the applycal task. Since applycal applies a calibration to the DATA column and stores the calibrated visibilities in the CORRECTED column, the split task should first be used to create a new measurement set containing only the data to be rescaled in order to avoid overwriting the corrected column. A calibration table with the necessary complex gain factors can then be created using the gencal task and applied. The below python script shows an example of increasing the visibility amplitudes by 10%, which has been tested for CASA 5.6.1. In this example, the DATA column is used because it contains the calibrated data, that is, this measurement was generated by a previous run of split (or mstransform) that pulled from the CORRECTED column.

```python
# Relative change to visibility amplitude, in this case an increase of 10
rescale_factor=1.1

# Split out data
split(vis='original_data.ms',
datacolumn='DATA',
outputvis='rescaled_data.ms')

# Generate calibration table with complex gain factors to produce the desired rescaling.
gencal(vis='rescaled_data.ms',
caltab='rescale.cal',
caltab='rescale.cal',
parameter=[1.0/np.sqrt(rescale_factor),])

# Apply calibration table.
applycal(vis='rescaled_data.ms',
gaintable='rescale.cal')
```
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