The JCMT Transient Survey: Data Reduction and Calibration Methods

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Abstract

Though there has been a significant amount of work investigating the early stages of low-mass star formation in recent years, the evolution of the mass assembly rate onto the central protostar remains largely unconstrained. Examining in depth the variation in this rate is critical to understanding the physics of star formation. Instabilities in the outer and inner circumstellar disk can lead to episodic outbursts. Observing these brightness variations at infrared or submillimeter wavelengths constrains the current accretion models. The JCMT Transient Survey is a three-year project dedicated to studying the continuum variability of deeply embedded protostars in eight nearby star-forming regions at a one-month cadence. We use the SCUBA-2 instrument to simultaneously observe these regions at wavelengths of 450 and 850 μm. In this paper, we present the data reduction techniques, image alignment procedures, and relative flux calibration methods for 850 μm data. We compare the properties and locations of bright, compact emission sources fitted with Gaussians over time. Doing so, we achieve a spatial alignment of better than 1″ between the repeated observations and an uncertainty of 2−3% in the relative peak brightness of significant, localized emission. This combination of imaging performance is unprecedented in ground-based, single-dish submillimeter observations. Finally, we identify a few sources that show possible and confirmed brightness variations. These sources will be closely monitored and presented in further detail in additional studies throughout the duration of the survey.

Key words: methods: data analysis – stars: formation – submillimeter: ISM – submillimeter: general – techniques: image processing

1. Introduction

Although many advances have been made in understanding low-mass star formation over the past 10 years (see, for example, di Francesco et al. 2007; Ward-Thompson et al. 2007a; André et al. 2014), the manner in which mass assembles onto a forming star remains a crucial open question. As Kenyon et al. (1990) first demonstrated, assuming the mass accretion process onto a young star occurs at a constant rate (steady inside-out collapse; Shu et al. 1987) gives rise to “the luminosity problem”; the empirical result that the median protostellar luminosity is measured to be approximately an order of magnitude less than the expected value. In recent years, this problem has been confirmed and emphasized by Spitzer Space Telescope observations, through which even lower luminosities have been discovered (see Dunham et al. 2008; Enoch et al. 2009; Evans et al. 2009; Dunham et al. 2013, 2014). One solution to this problem is that the accretion does not proceed at a constant rate. Rather, it occurs during episodic events that may be accompanied by outbursts that can be detected at infrared, submillimeter, and sometimes optical wavelengths (see McKee & Offner 2011; Johnstone et al. 2013; Scholz et al. 2013). There is indirect evidence that episodic accretion occurring while a protostar is still deeply embedded in its nascent gas and dust is an early phase of the more evolved FU Orionis (FUors; Herbig 1977, see also Hartmann & Kenyon 1985) sources (Audard et al. 2014; Dunham et al. 2014). The physical mechanism responsible for a continuum outburst detected at the submillimeter wavelengths of interest to this survey is reradiation from heated dust grains in the surrounding protostellar envelope. Outside of the JCMT Transient Survey, there have already been two millimeter sources (both embedded protostars) that have shown direct evidence of an active burst accretion phase accompanied by a dramatic brightening: HOPS 383 in Orion (Safron et al. 2015; using Atacama Pathfinder Experiment and SCUBA archive data) and MM1 in NGC6334I (Hunter et al. 2017; using Atacama Large Millimeter/submillimeter Array and Submillimeter Array data).
The JCMT Transient Survey (G. Herczeg et al. 2017, in preparation) is a three-year project dedicated to observing continuum variability in deeply embedded protostars at submillimeter wavelengths with the Submillimetre Common User Bolometer Array 2 (SCUBA-2; Holland et al. 2013). To this end, we are monitoring eight regions selected from the JCMT Gould Belt Survey (GBS; Ward-Thompson et al. 2007b) that have a high density of known protostellar and disk sources (young stellar object classes 0 to II and flat spectrum; see Lada 1987; Andre et al. 1993; and Greene et al. 1994) at an approximately 28-day cadence whenever they are observable in the sky. SCUBA-2 uses approximately 10,000 bolometers subdivided into two arrays to observe at both 450 and 850 μm simultaneously. While we expect sources undergoing an accretion burst event to show a stronger signal at 450 μm (Johnstone et al. 2013), in this paper we focus only on the 850 μm data. The noise levels in 450 μm maps are much more dependent on the weather than their 850 μm counterparts, causing the signal-to-noise ratio (S/N) to fall dramatically when there is more water vapor in the atmosphere. In addition, the beam profile is less stable than at 850 μm (as shorter wavelengths are more susceptible to dish deformation and focus errors; for more information, see Dempsey et al. 2013), requiring careful attention in order to make precise measurements of compact objects. We thus start here by defining the 850 μm calibration, and we will use this knowledge to calibrate the 450 μm data at a later date. As the survey matures and precise 450 μm data calibration is achieved, these simultaneous observations will provide further confirmation of significant variations.

In order to track the peak brightnesses of submillimeter emission sources over each epoch, we test and employ a robust data reduction method and use multiple observations of the same regions to derive postreduction image alignment and relative flux calibration techniques. Reducing SCUBA-2 data is a complex process with several user-defined parameters that affect the final image produced (for detailed information on SCUBA-2 data reduction procedures, see Chapin et al. 2013). A large amount of work has been invested in understanding the optimal data reduction parameters to use for differing science goals (see, for example, Mairs et al. 2015) depending on the scan pattern of the telescope and the amount of large-scale structure that needs to be robustly recovered. In all cases, the nominal JCMT pointing error is 2′′–6′′ (East Asian Observatory staff, private communication), and the flux calibration is uncertain to ~5%–10% (Dempsey et al. 2013; see also Section 4.2). While this is sufficient for most projects that use JCMT data, both of these uncertainties can be improved upon when there are multiple observations of regions with bright sources taken in a consistent manner. In this work, we seek to improve both the spatial alignment and the flux calibration of the JCMT Transient Survey data by approaching the problem from a relative point of view.

Properly matching faint potential protostellar sources over the observed epochs and coadding those observations with high precision for the highest S/N requires subpixel accuracy (≪3″ at 850 μm) in the spatial alignment. Similarly, if we were to use the nominal flux calibration, where the uncertainty is taken to be σ ~ 10%, the flux would need to vary by 30%–50% for a transient event to be deemed significant (3–5σ). Thus, our goal is to reduce this uncertainty by a factor of 3–5 (i.e., σ ~2%–3%) by considering relative brightness changes over time and ignoring the absolute flux calibration. We will then be able to measure flux variations of ~10% to be statistically significant (>3σ). Several models predict smaller flux variations due to episodic accretion over few-year timescales to occur much more frequently than large flux variations (see, for example, Bae et al. 2014; Vorobyov & Basu 2015; G. Herczeg et al. 2017, in preparation). Observations like those performed throughout the JCMT Transient Survey will help constrain the current models. The techniques we have developed here can be applied to any JCMT data obtained in a similar manner, including archival data obtained by the GBS (follow-up analysis by S. Mairs et al. 2017, in preparation). Thus, we can use successfully align and relatively flux calibrate archival data such as those that were obtained by the GBS, and we include these data in a follow-up analysis (S. Mairs et al. 2017, in preparation).

This paper is organized as follows: In Section 2 we summarize the details of our SCUBA-2 observations. In Section 3 we outline our data reduction methods and showcase four tests we performed that altered the amount of large-scale structure recovered in a given map and the initial priors offered to the map-making pipeline in order to select the most robust techniques for our purpose of detecting transient events in deeply embedded protostars. In Section 4 we detail our source extraction, postreduction spatial alignment, and relative flux calibration methods applied to all current JCMT Transient data. In Section 5, we present an analysis on the recovered compact emission sources and highlight objects of interest, including the first demonstrably variable source in our survey (H. Yoo et al. 2017, in preparation). Finally, we present our conclusions in Section 6.

2. Observations

The JCMT Transient Survey observations are performed simultaneously at 450 and 850 μm with effective beam sizes of 9′′8 and 14′′6 (Dempsey et al. 2013), respectively, using the Submillimetre Common User Bolometer Array 2 (SCUBA-2; Holland et al. 2013). We use the pong 1800′′ mapping mode (Kackley et al. 2010), which yields circular maps 0.5″ in diameter called “pongs.” Each pixel (3′′ at 850 μm, 2′′ at 450 μm) contains the signal from several bolometers as the telescope scans across the sky, changing direction when it reaches the boundary of the circular field. This scan pattern ensures that each part of the field is observed from multiple position angles, resulting in the recovery of real astronomical structure while short timescale variations due to the atmosphere are attenuated. Eight nearby (<500 pc) regions selected from the GBS (Ward-Thompson et al. 2007b; G. Herczeg et al. 2017, in preparation) are each monitored at an approximate 28-day cadence whenever they are observable in the sky. Contained within these regions are a total of 1749 young stellar objects (YSOs) identified by Spitzer Space Telescope (Megeath et al. 2012; Dunham et al. 2015) and Herschel Space Observatory (Stutz et al. 2013) observations. Of these, 344 YSOs are identified as Class 0/I or Flat Spectrum protostars, while the remaining 1405 are identified as Class II (disk) sources (G. Herczeg et al. 2017, in preparation). Table 1 shows a list of the regions and their central coordinates along with the average 850 μm rms noise measured in the individual maps (see Appendix A for detailed information on each individual observation). Note that Serpens South has diffuse structure throughout the map, even near the edges of the field, and, as a
Table 1
Summary of the Observed JCMT Transient Survey Fields between the First Observations on 2015 December 22 and 2017 March 1

| Region         | Central R.A. (J2000) | Central Decl. (J2000) | Number of Epochs | Average 850 μm Noise (mJy beam⁻¹) | Std. Dev. 850 μm Noise (mJy beam⁻¹) | Noise in the Coadd (mJy beam⁻¹) |
|----------------|----------------------|-----------------------|-----------------|-----------------------------------|-------------------------------------|--------------------------------|
| Perseus:       | 03:28:54             | +31:16:52             | 10              | 12.26                             | 0.40                                | 3.92                           |
| NGC 1333       |                      |                       |                 |                                   |                                     |                                |
| Perseus: IC 348| 03:44:18             | +32:04:59             | 9               | 12.18                             | 0.43                                | 4.30                           |
| Orion:         | 05:35:33             | −05:00:32             | 9               | 11.72                             | 0.54                                | 4.19                           |
| Orion: NGC 2024| 05:41:41             | −01:53:51             | 11              | 11.29                             | 0.40                                | 4.32                           |
| Orion: NGC 2068| 05:46:13             | −00:06:05             | 10              | 11.75                             | 0.38                                | 3.85                           |
| Ophiuchus: Core| 16:27:05             | −24:32:37             | 8               | 13.35                             | 0.75                                | 5.00                           |
| Serpens: Main  | 18:29:49             | +01:15:20             | 9               | 12.01                             | 0.27                                | 4.54                           |
| Serpens: South | 18:30:02             | −02:02:48             | 9               | 14.56                             | 1.18                                | 4.72                           |

Notes.

a Only observations between 2015 December 22 and 2017 March 1 are included.
b These measurements of the 850 μm noise levels are based on a point-source detection in a single observation using 3″ pixels and a 14″ FWHM beam.
c The reduction method R3 was used to derive these noise estimates (see Section 3).
d The standard deviation of the average 850 μm noise across all epochs.

result, the measured noise is slightly higher than in the other regions. There are five weather grades defined for JCMT observations from Band 1 (very dry: \( \tau_{225 \text{ GHz}} < 0.05 \), where \( \tau_{225 \text{ GHz}} \) is the zenith opacity of the atmosphere at 225 GHz) to Band 5 (very wet: \( \tau_{225 \text{ GHz}} > 0.2 \)). All of the observations performed in this survey were taken in either Band 1, Band 2, or Band 3 weather (\( \tau_{225 \text{ GHz}} < 0.12 \)) as measured by the JCMT Water Vapour Radiometer (Dempsey & Friberg 2008). The observing time per observation is set to 20–40 minutes, depending on the weather band, to maintain a similar noise quality of \( \sim 10 \) mJy beam⁻¹ at 850 μm (see Table 1).

Due to the higher telluric absorption (see Dempsey et al. 2013) and varying PWV (precipitable water vapor), the 450 μm observations have noise values 10–40 times higher than the 850 μm observations, so throughout this paper we focus on the latter. Observations began in 2015 December and are expected to continue until 2019 January. Here, we present results between the first observations in 2015 December and 2017 March 1.

3. Data Reduction Methods

The data reduction procedure was performed using the iterative map-making technique MAKEMAP (explained in detail by Chapin et al. 2013) in the SMURF package (Jenness et al. 2013) found within the STARLINK software (Currie et al. 2014). Briefly, MAKEMAP begins with the raw power detected by the telescope as a function of time throughout the duration of the observation and iteratively works to recover the astronomical signal by modeling and subtracting different sources of noise. First, general fixes (such as removing noise spikes, ensuring continuity, and apodizing the edges of the bolometer time series) and a flat-field correction are applied. Then, the program removes the common mode (COM) noise. This type of noise, the large majority of which is caused by atmospheric emission, dominates the astronomical features we seek to study by causing a significant fraction of SCUBA-2’s bolometers to acquire the same signal. As SCUBA-2 scans across a region of the sky at a constant speed, the power received over a given time interval is directly correlated with a spatial scale. Thus, removing the common mode noise results in a loss of extended, faint structure in the final maps produced, while the more compact, bright structure can be more accurately recovered. For an overview of the GBS for their Legacy Release 1 (GBS LR1) filtering parameters as well as results from testing the completeness of this method using artificial sources, see Mairs et al. (2015).

Next, an atmospheric extinction model is applied based on the amount of PWV that was measured during the observation, and a second filtering of the data is applied to remove any residual low-frequency \( 1/f \) noise that was missed by the common mode subtraction. The extent of the final spatial filtering executed in this step is defined by the user. Generally, the largest recoverable scales are \( \sim 600″ \) before the atmospheric signal becomes significant.

Finally, the astronomical signal is estimated, and the residual white noise is compared to the previous iteration. The iterative solution converges when the difference in individual pixels changes on average by a user-defined threshold percentage of the rms noise present in the map (we select a value of <0.1%). The maps produced are originally in units of picowatts (pW) but are converted to mJy arcsec⁻² using the standard 850 μm aperture flux conversion factor 2340 mJy pW⁻¹ arcsec⁻² and 4710 mJy pW⁻¹ arcsec⁻² at 450 μm (Dempsey et al. 2013). In the case of the JCMT Transient Survey, the final maps are gridded to 3″ pixels for the 850 μm data and 2″ pixels for the 450 μm data.

To apply additional constraints to the solution derived by MAKEMAP, the user can also supply an external mask that surrounds the astronomical signal deemed to be significant. To construct an external mask, the individual maps produced by the iterative mapmaker are coadded in order to achieve a higher S/N. The resulting image is used to define the regions of genuine astronomical emission (pixels with an S/N of at least 3 are generally deemed significant). This mask is then used in a second round of data reduction in order to recover better any faint and extended structure.

MAKEMAP has over 100 user-defined parameters that allow full control over each step of the iterative process. Many parameters will cause negligible changes in the final maps produced, but some will cause significant differences, such as the extent of spatial filtering the user applies. For the JCMT Transient Survey, we begin with the robust data reduction parameters derived by the GBS LR1 data set as described in Mairs et al. (2015). To ensure, however, that we produced the best-calibrated maps that would allow for the detection of the
variability of embedded protostars, we tested the effects of altering the size of the spatial filter applied to the data to determine whether or not it was beneficial to apply additional constraints to MAKEMAP by using an external mask.

To this end, we performed four individual data reductions labeled R1, R2, R3, and R4, yielding four sets of maps exhibiting different models of the recovered, astronomical structure:

1. R1: An effective spatial filter of 200″ was applied, and no external mask was used.
2. R2: An effective spatial filter of 600″ was applied, and no external mask was used.
3. R3: An external mask was constructed from a coadd of the R1 reduction and was used to constrain the solution derived by MAKEMAP. Thus, the structure was filtered to 200″.
4. R4: Similarly to R3, an external mask was constructed from a coadd of the R2 reduction and applied to the data. Thus, the structure was filtered to 600″. This reduction is the same as the GBS LR1 data release (Mairs et al. 2015).

Figure 1 shows an example of a single observation of the Ophiuchus Core region (see Table 1). The top two panels show the resulting maps produced by reductions R3 (left) and R4 (right), while the bottom two panels show the subtraction of the R3 image from the R4 image (left) to highlight the effect of

Figure 1. Top: a single 850 μm observation of the Ophiuchus Core region reduced using reduction methods R3 (left) and R4 (right). Bottom: reduction R4 minus reduction R3 (left) and reduction R4 minus reduction R2 (right). Note that the two small, bright sources seen in the bottom of the R3 and R4 maps are roughly point-like.
changing the effective spatial filter and the subtraction of the R2 image from the R4 image (right) to highlight the effect of the external mask. Though more extended structure is present in the R2 and R4 maps, the compact structure is recovered whether a 200′′ or a 600′′ filter is used. For the extended emission reconstructions, the mask returns additional flux, some of which appears pedestal-like. As Mairs et al. (2015) discuss, the amount of extended structure that is recovered can produce slightly different results for the compact structure present in the map as the larger-scale background may add a pedestal value to the flux. We minimize the effect of the pedestal by using a localized peak extraction algorithm (described in Section 4 and Appendix B) that filters out the extended background.

The dominant uncertainty between these different reduction methods is how the recovered extended structure and external masks alter the fit to compact emission sources. The measurement of the peak brightness of a source relies on a consistent procedure from observation to observation in conjunction with the optimal data reduction method. By fitting Gaussian profiles to compact emission sources and comparing their centroid positions and peak brightnesses (described in detail in Section 4), we determine reduction R3 to be the most stable for our purposes (although all four reductions work reasonably well). The external mask limits the flux distribution during the map-making procedure, while the harsher filter (200′′ as opposed to 600′′) subdues large-scale structure, which is not expected to vary (but is hard to recover due to signal from the atmosphere and the instrumentation).

SCUBA-2’s 850 μm filter coincides with the broad \(^{12}\text{CO}(J = 3 – 2)\) emission line. No attempt has been made to remove this signal. Excess flux, however, will not affect our ability to measure precisely the variability of deeply embedded protostars. As Drabek et al. (2012) and Coudé et al. (2016) discuss, the CO\((J = 3 – 2)\) line contributes only low-level emission (≤20%) except for a few sources of stellar outflow. In addition, as Mairs et al. (2016) show, the peak brightnesses of compact sources are not affected by the removal of the emission line.

4. Postreduction Calibrations

Since the JCMT Transient Survey is interested in measuring the fluxes of individual compact sources over time, it is important to take into consideration both the pointing uncertainty of the telescope (expected to be 2–6 arcsec; East Asian Observatory staff private communication) as well as the flux calibration uncertainty (expected to be ~5%–10%; see Dempsey et al. 2013). To this end, we perform two postreduction calibrations: (1) we derive and apply a pointing correction to more precisely align the maps with one another, and (2) we derive and apply a relative flux calibration factor for each image produced in order to consistently compare a given source from observation to observation. Since both of these calibrations are relative corrections for each region, we can use the most robust, compact emission sources present in each map to calibrate self-consistently. The first step is to identify the appropriate calibrator sources in each of the eight regions.

There are many different publicly available algorithms designed to extract structure from a given region (for example, see GAUSSCLUMPS, Stutzki & Guesten 1990; CLUMPFRIND, Williams et al. 1994; ASTRODENDRO, Rosolowsky et al. 2008; GETSOURCES, Men’shchikov et al. 2012; and FELLWALKER, Berry 2015). Each method combines detected emission differently based on user-supplied criteria, so the use of such algorithms requires discernment and a goal-based approach. In this work, we are interested in accurately determining the brightness of localized, compact sources in dust emission convolved with the JCMT beam, which we expect to have approximately Gaussian features. The most robust (often isolated) Gaussian sources will be used for image calibration. To this end, we have selected the algorithm GAUSSCLUMPS (Stutzki & Guesten 1990) to identify and extract sources in each observation of a given field as this program is designed to robustly characterize Gaussian structure and subtract background structure, such as pedestals. Specifically, we use the STARLINK software (Currie et al. 2014) implementation of GAUSSCLUMPS found within the CUPID (Berry et al. 2007) package. For more information on GAUSSCLUMPS, refer to Appendix B.

4.1. Image Alignment

To perform the postreduction relative image alignment, we focus on the 850 μm data. The noise in this data set is measured to be more than an order of magnitude below its 450 μm counterpart (due to the effect of PWV in the atmosphere), and the beam profile has greater stability, allowing us to more reliably fit the compact emission sources. The 450 and 850 μm data are, however, taken simultaneously, so the same alignment correction is applied to both data sets. The alignment procedure we apply to the data consists of five steps:

1. We label the first observation of a given field the “reference observation.” Then, we smooth the map with a 6′′ Gaussian kernel to mitigate noise fluctuations. We identify and fit Gaussians to all of the sources brighter than 200 mJy beam\(^{-1}\) and with radii less than 10′′ in the reference observation using the source extraction algorithm GAUSSCLUMPS (Stutzki & Guesten 1990). The radius of a source, \(r\), is defined as \(r = \sqrt{\text{FWHM}_1 \times \text{FWHM}_2 / 2}\), where the FWHM terms are the FWHM of the fitted two-dimensional Gaussian. Fitting Gaussians to bright sources allows us to measure the centroid location of the sources to subpixel accuracy. For more information on how GAUSSCLUMPS was executed, see Appendix B.

2. For later observations, we also smooth the maps and identify and fit Gaussians to all of the sources brighter than 200 mJy beam\(^{-1}\) and with radii less than 10′′ using GAUSSCLUMPS in the same manner as for the reference observation.

3. We next match each source identified in the reference catalog to the nearest source in the later catalog (the peak location sources must not differ by more than 10′′, given an expectation that the alignment offset is better than this value).

4. We then perform a check to ensure that we have matched the reference sources to the correct corresponding sources in the later catalog by employing a simple test. Plotting the relative right ascension offset against the relative declination offset for all of the sources, we search for outliers by applying the condition that the resultant offset of every source must be within 4′′ of the resultant offset of any other source (see Figure 2). Note that 4′′ was chosen after extensive testing across all eight regions.
revealed that this threshold consistently eliminated outliers. If this condition fails, we exclude that source from the final step. In this way, any moving sources or spurious detections will be discounted from our analysis.

5. Finally, we average the right ascension and declination offsets of the matched sources to find the difference between the positions of the later observation and the reference observation. We then apply this offset by rereducing the later observation and correcting the pointing using MAKEMAP’s pointing parameter. In this way, both the reference and the later observations will be consistently aligned, processed, and gridded to the same world coordinate system grid.

Figure 3 shows the results of applying the postreduction alignment to the JCMT Transient Survey observations using reduction R3 (all four reduction methods show consistent results; see Appendix A). The black histogram shows the original pointing uncertainty, while the blue histogram shows the corrected pointing uncertainty. By reliably fitting bright peaks and matching their centroids from observation to observation, we have achieved a mean positional uncertainty of 0.045 (less than one-sixth the width of an 850 μm pixel) with a standard deviation of 0.73. In nearly all cases, the images are aligned to better than 1″. The few fields that exhibit a slightly higher uncertainty come from the NGC 2024 region, which contains more clustered sources mixed with larger-scale structure (see Figure 4 for an example of the clustered emission in NGC 2024, and see G. Herczeg et al. 2017, in preparation, for coadded images of all eight fields). Isolated, bright emission sources have fewer fitting uncertainties and therefore produce the best alignments. The alignment of the maps is now part of an automated routine run at the East Asian Observatory (EAO) immediately after the observations are taken at the telescope. The final aligned images and GAUSSCLUMPS catalogs are deposited in a shared directory that team members can access.

In addition to this image alignment procedure, an independent method based on the cross-correlation (CC) of the observations was also tested and found to produce consistent results (see Appendix C). As the survey matures, we will be exploring this alternate technique and refining our methodology to further improve our alignment calibration.

4.2. Relative Flux Calibration

After cataloging the sources in the reference observation as well as the subsequent aligned observations, we derive and apply a relative flux calibration factor to each observation in order to plot accurately the brightness variations of a given object over all epochs. The JCMT has an intrinsic absolute flux calibration of ~5%–10% (Dempsey et al. 2013), but we are focused only on the relative brightness changes from epoch to epoch. This allows us to achieve more accurate measurements of the variability in a given field. The procedure to flux calibrate our images consists of six steps:

1. Beginning with the same calibrator sources that we extracted to perform the spatial alignment of the maps (described in Section 4.1), we select the subset that have peak brightnesses over 500 mJy beam\(^{-1}\) and appear in every single observation of a given region. The choice of 500 mJy beam\(^{-1}\) is based on a desire to reach a relative
brightness calibration of ∼2%, and the typical noise is ∼10 mJy beam$^{-1}$ in each image (see Table 1), yielding an S/N for the minimum brightness peaks of ∼50:1. We first calculate the average peak brightness over all epochs to remove the uncertainty in flux related to individual measurements and then normalize the observed source peak brightnesses in each observation to their respective averages.

2. We then compare the brightness of each extracted source with respect to each of the others by taking the ratio of their normalized peak brightnesses and plotting the result for each epoch (for example, see Figure 5). If a given pair of sources gets brighter or dimmer together from epoch to epoch, due to calibration uncertainties, we would expect the ratio of their normalized peak brightnesses over time to show little scatter.

3. We next measure the amount of scatter in the ratio between two sources by calculating the standard deviation in the ratio of normalized peak brightnesses over time. For every pair of sources, we can plot the measured standard deviation. In Figure 6, we show the results of a simple model of the standard deviations measured for pairs of sources by applying a Gaussian error of the value indicated to 1000 sources of peak brightness 1.0 and comparing their expected normalized peak brightness ratios over eight epochs. Overlaid on this figure are the measured standard deviations of the normalized source peak brightness ratios for all nine potential calibrator sources in all eight observations of the Ophiuchus Core region. Note that as more epochs are observed, the central part of the curve flattens, approaching a value of $\sqrt{2} \times$ error. Nine potential calibrator sources were found, yielding 36 pairs. The largest Family of sources consistent with one another (standard deviations less than 0.06, the threshold indicated by the dashed black line) are the flux calibrator sources we select to perform the correction. In this case, four sources met the criteria to join the flux calibrator Family.

4. We next identify the largest set of sources wherein every pair has a standard deviation below a threshold set to 0.06. We call this set of stable sources a Family. We choose 0.06 through comparison with model curves in Figure 6 and as a compromise between decreasing the number of family members versus increasing the reliability of the calibration. Thus, all Family members satisfy the threshold when compared against each other. These sources are considered nonvarying and appropriate for the relative flux calibration of each epoch. This threshold was chosen after extensive testing for the optimal number of sources contained within the Family across all observed regions.
5. For each epoch, the flux calibration factor by which we divide every pixel is the average normalized peak brightness over all the sources within the Family during that observation. These factors are plotted in the left panel of Figure 7. In the figure, black indicates all observations taken before 2017 March 1, while gray indicates observations taken after the filter change on SCUBA-2 in 2016 November. The standard deviation of a Gaussian fit to all the data is 8%, as expected (Dempsey et al. 2013).

6. The uncertainty in the derived flux calibration factor is taken to be the error in a given measurement of the normalized peak brightness of an individual source, which is calculated by finding the standard deviation of the normalized peak brightnesses of all the calibrator sources. This uncertainty is plotted in the right panel of Figure 7. Note that the uncertainty peaks at approximately 2%. This is, however, the uncertainty per source, while the error in the mean scales with the square root of the number of calibrator sources detected. Again, all four tested reductions show consistent results (e.g., compare the R3 flux calibration results with R4 in Appendix A), though the R3 reduction is most robust for the JCMT Transient Survey science goals.

The highest flux calibration factor uncertainty is found in the NGC 2024 region for the same reasons the residual offset in the aligned maps is larger; the calibrator sources identified in NGC 2024 are found within the extended structure where our Gaussian fitting routine encounters more uncertainty. Overall, the flux calibration uncertainties are very low (~2%–3%), allowing the JCMT Transient Survey team to robustly detect variations in peak brightness of the most prominent sources to the level of ~10%. Previously, Haubois et al. (2012) achieved this relative calibration accuracy over a 5 day monitoring campaign of Sagittarius A* using the Atacama Pathfinder Experiment instrument at the Llano de Chajnantor Observatory. These small uncertainties, however, are unprecedented in ground-based, single-dish submillimeter observations for such a wide range of consistent observations. In addition, we fit many sources in each field, which allows us to detect sufficiently significant brightness variations on the first epoch they occur. Note that since we determine each epoch’s flux calibration factor in a relative sense, the SCUBA-2 filter change in 2016 does not affect our results. The absolute brightness measurements, however, depend on the flux conversion factors (see Section 3). The filter change is expected to cause a small but detectable change in these values, but this has not yet been quantified by the observatory.

Our calibration is only expected to improve as we include future epochs and refine our methods throughout the duration of the survey. With additional epochs, we will be able to coadd subsets of our observations to increase our sensitivity at the cost of a lower cadence. Presently, we are working to automate the flux calibration procedure such that it can also be run directly after an observation undergoes the data reduction and alignment procedures at the EAO. For a given observation, the aligned and flux calibrated data are presently available to team members within 24–48 hr.

5. Discussion

The goal of this calibration work is to extract robust, nonvarying sources from SCUBA-2 maps and apply the spatial alignment and flux calibration methods. The majority of this process involves excluding sources from flux calibrator Families that do not meet our set of criteria. These excluded sources, however, are of particular interest to the JCMT Transient Survey as they may be transient.

Figures 8 and 9 show the measured fractional variation in the fluxes (standard deviation) of each observed source across all epochs over which it was observed, ordered by source brightness. For a source to be included on these plots, it must be detected in every epoch of the given region. Thus, there are many additional, potentially interesting submillimeter sources that are not included in these figures as our focus is on potential calibrators. A source may not be detected in a given epoch for two reasons: (1) it has properties near enough to the detection threshold that it is too faint or too extended on some observation dates but not on others (a source in a clustered environment is difficult to fit, which may...
cause the shape to change), or (2) the peak brightness of the source may vary such that it was too faint to be detected at the time of the reference observation but it was bright enough at a later date (or vice versa). The sources in both scenarios are of little importance to the flux calibration since we only want to use the most robust sources available. Detecting the sources in the second scenario is one of the goals of the JCMT Transient Survey, and follow-up studies are currently underway to quantify their number and amplitude (for example, S. Mairs et al. 2017, in preparation). Including all observations of all eight regions, using our source extraction methods based on detecting compact structure and fitting Gaussian profiles with GAUSSCLUMPS as detailed in Appendix B, we see a total of 265 unique areas of significant, localized emission (see Table 2). This number is expected to vary depending on the source identification procedure used and the amount of data received.

The lower bound of the shaded regions in Figures 8 and 9 shows the average noise in each region (see Table 1) as a percentage of the mean peak brightness, while the upper bound represents the noise multiplied by a factor of two to take into consideration additional uncertainties due to, for example, the source fitting procedure. In general, we expect fainter sources to approximately follow the shaded region, whereas we expect Family members to lie farther to the right and display low standard deviations dominated by the Gaussian fitting uncertainties. The vertical dotted line shows the minimum peak brightness threshold for a source to be considered a member of a Family (500 mJy beam$^{-1}$), and the horizontal dashed line shows the mean standard deviation of the Family members in that specific region.

Most of the sources behave as expected for objects that do not vary with time. There are, however, a few notable exceptions. The OMC 2/3 and NGC 2024 fields are where localized Gaussian profiles are extracted from particularly clustered and confused emission (see, for example, Figure 4). These two regions have the highest number of relatively bright sources not included in their Families, most likely due to the

Figure 8. The standard deviation in the peak brightness vs. the mean peak brightness of a source for four of the Transient fields. The horizontal error bars indicate the range of peak brightnesses observed across all dates. Filled triangles represent Family members, while empty triangles represent other sources not included in the flux calibration. The vertical dotted line indicates the minimum brightness threshold to be considered a member of a Family. The horizontal dashed line shows the average standard deviation in the peak brightness of all the Family sources. The lower bound of the shaded region shows the average noise as a percentage of source peak brightness, and the upper bound of the shaded region assumes the noise is higher by a factor of two.
source extraction procedure but also possibly due to intrinsic variability. GAUSSCLUMPS is able to extract and fit well-isolated, compact emission sources, while sources extracted from clustered regions have more uncertainty. Depending on the morphology of the surrounding background structure, emission from multiple sources can be blended, which causes some sources to deviate from Gaussian profiles, fluctuating in elongation from epoch to epoch as the algorithm attempts to separate the significant structure from the background. Examples of these sources include the two that meet the minimum brightness threshold but fail to be included in a Family in NGC 1333 (Figure 8, top right), the brightest source in the Serpens Main region (Figure 9, bottom left), and the source on the Family brightness threshold in the Serpens Main region (Figure 9, bottom left). Since this paper is concerned with calibration, we simply ignore these more complicated sources. In future papers, however, we will adapt techniques to better identify variability in the most crowded regions in our fields. In general, sources that fail the flux calibrator criteria are lower peak brightness, as expected (see Figure 10).

Another reason a source may significantly deviate from what we expect and fail to be included in a Family is that it is undergoing an observable physical variation. Our relative flux calibration algorithm has been designed to exclude sources that are varying so that their contribution would not suppress the signal we seek to study. One variable source has been identified (see Figure 9, bottom left) and verified over multiple observations in our data set (for more detail on this source, refer to H. Yoo et al. 2017, in preparation). A careful but cursory analysis of each source that was detected in every observation and was excluded from a Family has been carried out, and no other clear and robust detections of significant variability have so far been identified. Investigations will continue, however, to uncover any long-term trends. In addition, there are many sources present in each map that are not presented in this paper. Analyses employing different source extraction methods as well as procedures that consider the variability of faint sources are currently underway (for example, S. Mairs et al. 2017, in preparation; H. Yoo et al. 2017, in preparation).
| Region   | Date     | Scan | $\tau$ | 850 $\mu$m Noise$^{e}$ | Number of Sources above $10\sigma_{\text{rms}}$ | Number of Alignment Sources | Number of Family Members |
|----------|----------|------|--------|-------------------------|-------------------------------|----------------------------|--------------------------|
| IC 348   | 20151222 | 19   | 0.06   | 12.54                   | 9                            | 6                          | 3                        |
| IC 348   | 20160115 | 22   | 0.07   | 9.99                    | 12                           | 6                          | 3                        |
| IC 348   | 20160205 | 18   | 0.04   | 12.79                   | 12                           | 6                          | 3                        |
| IC 348   | 20160226 | 20   | 0.05   | 12.39                   | 13                           | 5                          | 3                        |
| IC 348   | 20160318 | 27   | 0.05   | 11.1                    | 12                           | 5                          | 3                        |
| IC 348   | 20160417 | 09   | 0.04   | 11.0                    | 13                           | 5                          | 3                        |
| IC 348   | 20160826 | 40   | 0.08   | 14.33                   | 12                           | 6                          | 3                        |
| IC 348   | 20161126 | 22   | 0.05   | 12.29                   | 14                           | 6                          | 3                        |
| IC 348   | 20170209 | 28   | 0.09   | 13.17                   | 12                           | 5                          | 3                        |
| NGC 1333 | 20151222 | 18   | 0.06   | 12.22                   | 39                           | 36                         | 7                        |
| NGC 1333 | 20160115 | 10   | 0.08   | 11.76                   | 40                           | 29                         | 7                        |
| NGC 1333 | 20160205 | 17   | 0.04   | 12.99                   | 39                           | 29                         | 7                        |
| NGC 1333 | 20160226 | 22   | 0.05   | 12.83                   | 13                           | 6                          | 3                        |
| NGC 1333 | 20160318 | 27   | 0.05   | 11.1                    | 12                           | 5                          | 3                        |
| NGC 1333 | 20160417 | 09   | 0.04   | 11.0                    | 13                           | 5                          | 3                        |
| NGC 1333 | 20160826 | 40   | 0.08   | 14.33                   | 12                           | 6                          | 3                        |
| NGC 1333 | 20161126 | 22   | 0.05   | 12.29                   | 14                           | 6                          | 3                        |
| NGC 1333 | 20170209 | 28   | 0.09   | 13.17                   | 12                           | 5                          | 3                        |
| OMC 2/3  | 20151222 | 18   | 0.06   | 12.22                   | 39                           | 36                         | 7                        |
| OMC 2/3  | 20160115 | 10   | 0.08   | 11.76                   | 40                           | 29                         | 7                        |
| OMC 2/3  | 20160205 | 17   | 0.04   | 12.99                   | 39                           | 29                         | 7                        |
| OMC 2/3  | 20160226 | 22   | 0.05   | 12.83                   | 13                           | 6                          | 3                        |
| OMC 2/3  | 20160318 | 27   | 0.05   | 11.1                    | 12                           | 5                          | 3                        |
| OMC 2/3  | 20160417 | 09   | 0.04   | 11.0                    | 13                           | 5                          | 3                        |
| OMC 2/3  | 20160826 | 40   | 0.08   | 14.33                   | 12                           | 6                          | 3                        |
| OMC 2/3  | 20161126 | 22   | 0.05   | 12.29                   | 14                           | 6                          | 3                        |
| OMC 2/3  | 20170209 | 28   | 0.09   | 13.17                   | 12                           | 5                          | 3                        |
| NGC 1333 | 20151222 | 18   | 0.06   | 12.22                   | 39                           | 36                         | 7                        |
| NGC 1333 | 20160115 | 10   | 0.08   | 11.76                   | 40                           | 29                         | 7                        |
| NGC 1333 | 20160205 | 17   | 0.04   | 12.99                   | 39                           | 29                         | 7                        |
| NGC 1333 | 20160226 | 22   | 0.05   | 12.83                   | 13                           | 6                          | 3                        |
| NGC 1333 | 20160318 | 27   | 0.05   | 11.1                    | 12                           | 5                          | 3                        |
| NGC 1333 | 20160417 | 09   | 0.04   | 11.0                    | 13                           | 5                          | 3                        |
| NGC 1333 | 20160826 | 40   | 0.08   | 14.33                   | 12                           | 6                          | 3                        |
| NGC 1333 | 20161126 | 22   | 0.05   | 12.29                   | 14                           | 6                          | 3                        |
| NGC 1333 | 20170209 | 28   | 0.09   | 13.17                   | 12                           | 5                          | 3                        |
| NGC 2068 | 20160116 | 19   | 0.06   | 9.8                     | 15                           | 7                          | 3                        |
| NGC 2068 | 20160826 | 20   | 0.05   | 12.08                   | 31                           | 21                         | 8                        |
| NGC 2068 | 20160827 | 53   | 0.08   | 11.8                    | 31                           | 21                         | 8                        |
| NGC 2068 | 20161120 | 88   | 0.09   | 11.98                   | 30                           | 20                         | 8                        |
| NGC 2068 | 20161126 | 56   | 0.06   | 10.16                   | 30                           | 21                         | 8                        |
| NGC 2068 | 20170206 | 17   | 0.11   | 12.76                   | 32                           | 20                         | 8                        |
| NGC 2068 | 20170206 | 17   | 0.11   | 12.76                   | 32                           | 20                         | 8                        |
| Serpens Main | 20160202 | 54   | 0.09   | 12.11                   | 23                           | 20                         | 10                       |
| Serpens Main | 20160223 | 50   | 0.05   | 11.68                   | 22                           | 18                         | 5                        |
| Serpens Main | 20160317 | 51   | 0.04   | 12.2                    | 21                           | 14                         | 5                        |
| Serpens Main | 20160415 | 46   | 0.04   | 11.82                   | 22                           | 16                         | 5                        |
| Serpens Main | 20160521 | 39   | 0.08   | 14.01                   | 22                           | 15                         | 5                        |
| Serpens Main | 20160722 | 23   | 0.1    | 11.49                   | 23                           | 14                         | 5                        |
Table 2

(Continued)

| Region       | Date       | Scan | $\tau$ | 850 $\mu$m Noise$^b,c$ (mJy beam$^{-1}$) | Number of Sources above $10\sigma_{\text{rms}}$ | Number of Alignment Sources | Number of Family Members |
|--------------|------------|------|--------|----------------------------------------|-----------------------------------------------|----------------------------|--------------------------|
| Serpens Main | 20160827   | 12   | 0.09   | 11.32                                  | 24                                            | 15                         | 5                        |
| Serpens Main | 20160929   | 12   | 0.09   | 11.95                                  | 18                                            | 13                         | 5                        |
| Serpens Main | 20170222   | 70   | 0.1    | 11.47                                  | 26                                            | 12                         | 5                        |
| Serpens South | 20160202   | 58   | 0.09   | 11.27                                  | 39                                            | 35                         | 9                        |
| Serpens South | 20160223   | 65   | 0.05   | 18.66                                  | 39                                            | 32                         | 9                        |
| Serpens South | 20160317   | 52   | 0.04   | 11.41                                  | 34                                            | 25                         | 9                        |
| Serpens South | 20160415   | 48   | 0.04   | 11.57                                  | 38                                            | 29                         | 9                        |
| Serpens South | 20160521   | 44   | 0.07   | 12.61                                  | 38                                            | 27                         | 9                        |
| Serpens South | 20160721   | 11   | 0.08   | 19.42                                  | 41                                            | 31                         | 9                        |
| Serpens South | 20160827   | 17   | 0.09   | 17.05                                  | 43                                            | 32                         | 9                        |
| Serpens South | 20160929   | 18   | 0.08   | 11.34                                  | 39                                            | 30                         | 9                        |
| Serpens South | 20170222   | 81   | 0.1    | 17.68                                  | 36                                            | 28                         | 9                        |

Notes.

$^a$ The average 225 GHz zenith opacity measured throughout the duration of the observation.

$^b$ These measurements of the 850 $\mu$m noise ($\sigma_{\text{rms}}$) levels are based on a point source detection in a single observation using 3$''$ pixels and a 14$''$6 FWHM beam.

$^c$ The reduction method R3 was used to derive these noise estimates (see Section 3).

---

6. Conclusion

The primary goal of the JCMT Transient Survey is to detect variability in the brightness of deeply embedded protostars. The pointing accuracy of the JCMT is nominally 2–6 arcsec, while the nominal flux calibration uncertainty of 850 $\mu$m SCUBA-2 data is 8% (see Figures 3 and 7). In order to dramatically increase our sensitivity to variable signals, we have developed a calibration pipeline that further spatially aligns multiple observations of a given field and provides a relative flux calibration correction for bright, compact sources. We use the algorithm GAUSSCLUMPS (see Section 4 and Appendix B) to extract locations and peak brightnesses of emission objects in the 850 $\mu$m SCUBA-2 maps, and we apply minimum brightness (200 mJy beam$^{-1}$ for the spatial alignment and 500 mJy beam$^{-1}$ for the relative flux calibration) and maximum radius (10$''$) thresholds to ensure we have the best-fit objects in our sample. These methods could be applied to any submillimeter data with multiple observations of bright, compact objects. Our main results can be summarized as follows:

1. We thoroughly tested four different data reduction methods and found the most robust parameters for our scientific goals (reduction R3, see Section 3).
2. We achieve a subpixel alignment uncertainty of $\sim$1$''$ (see Figure 3 and Section 4.1), improving on the pointing error of the telescope by a factor of $\sim$4.
3. We achieve a relative flux calibration factor uncertainty of 2%–3% for bright sources (see Figure 3 and Section 4.1), improving on the native, absolute flux calibration uncertainty by a factor of $\sim$3. This is unprecedented in ground-based, single-dish submillimeter observations.
4. By analyzing the bright sources that are not included in flux calibrator Families, we have noted a variable source at 850 $\mu$m (H. Yoo et al. 2017, in preparation) and identified good source extraction practices for further analysis to improve the calibration procedure.

The JCMT Transient Survey is expected to continue through at least 2019 January, increasing the number of observed epochs for each region by a factor of 3 to about 30. Throughout this time, we will be working to improve the data reduction and calibration procedures (see Appendix C) in order to detect fainter signals and working to achieve similar results for the relative flux calibration uncertainty at 450 $\mu$m. By the end of the survey, we will have the deepest submillimeter maps of these eight regions, which will create many opportunities for additional science, including coadding across several epochs to uncover variability in fainter sources, but with a lower cadence.

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Facility: JCMT(SCUBA-2) (Holland et al. 2013).
Software: Starlink (Currie et al. 2014), Astropy (Astropy Collaboration et al. 2013), Python version 3.5, APLPy (Robitaille & Bressert 2012), Matplotlib (Hunter 2007).

Appendix A
Observational Data

Table 2 presents detailed information about all of the JCMT Transient Survey observations taken between 2015 December 22 (the beginning of the survey) and 2017 March 1. Reduction R3 is used in each case. Figure 11 highlights that the four tested data reduction methods produce consistent spatial alignment results overall, while Figure 12 shows that the R3 and R4 (and, by extension, R1 and R2) relative flux calibration results are also consistent.

Appendix B
GAUSSCLUMPS

GAUSSCLUMPS (Stutzki & Guesten 1990) identifies first the brightest peak in a user-supplied map and fits a 2D Gaussian profile to the surrounding structure with a least-squares method. If the structure is deemed to be real (i.e., not a spurious detection of a noise spike, a test that is based on a series of user-defined parameters), the fit is subtracted from the data, and the algorithm iteratively identifies and fits a Gaussian to the next brightest peak until all of the significant structure is identified. The algorithm is designed to weight the Gaussian fits to smaller-scale structures (at least the size of the instrument beam) such that locally peaked objects are preferred over underlying larger-scale features. Identified sources are allowed to overlap.

There are many user-defined parameters that control how GAUSSCLUMPS identifies structure as well as when it terminates after successfully extracting all of the emission found to be significant. Here, we summarize the main parameters we have used. For the parameters not listed, we simply use the default values:

1. BACKOFF = True. This parameter subtracts the background level from each identified emission source before calculating the sizes and centroid positions.
2. FwhmBeam = 5. This parameter defines the FWHM size of the JCMT beam in pixels. No Gaussians that are smaller than this will be considered robust. For the 850 μm data, we use a pixel size of 3″, while the data smoothed with a 6″ Gaussian kernel has an FWHM beam size of 15″8.

3. MaxBad = 0. This parameter determines the maximum fraction of bad pixels that can be included in an identified source.

4. MaxNF = 150. This parameter determines the maximum number of times the chi-squared between the Gaussian model and the data will be iteratively evaluated and adjusted.

5. MaxSkip = 20. This parameter sets the maximum number of consecutive failures to fit Gaussians. If GAUSSCLUMPS fails to fit a Gaussian to the data more than 20 consecutive times, the algorithm terminates.

6. Thresh = 10.0. This parameter defines the minimum peak brightness of a fitted Gaussian in units of the measured rms noise. Note that we also measure the rms noise for each map individually and supply that value to GAUSSCLUMPS' rms parameter.

The typical rms noise in a given 850 μm observation is ~10 mJy beam⁻¹ (see Tables 1 and 2), so we catalog sources with peak brightnesses above ~100 mJy beam⁻¹. Once we obtain the results from GAUSSCLUMPS, we apply an additional cull to the catalog to select the brightest locally peaked objects to select the image alignment and flux calibration sources. Based on a series of tests varying the minimum brightness threshold and maximum source radius of identified objects, we select sources with peak brightnesses greater than 200 mJy beam⁻¹ and radii less than 10″. We define the radius of a source to be \( r = \sqrt{\text{FWHM}_x \times \text{FWHM}_y / 2} \), where the \( \text{FWHM}_x \) terms are the FWHM of the two-dimensional Gaussian. For the flux calibration sources, we select sources with peak brightnesses greater than 500 mJy beam⁻¹.

The cross-correlation method is advantageous to the GAUSSCLUMPS method as the GAUSSCLUMPS method

Appendix C

Alternative Alignment Method

As an alternative approach to calibrating the image alignment, we present a method currently under investigation based on cross-correlation between epochs. In this section we present results from the R1 850 μm reductions, but this CC method has proven to be successful for all four of the 850 μm reductions.

The CC method computes the CC between a reference epoch to each succeeding science epoch:

\[
\text{cor}(\text{R.A.}, \text{decl.}) = \sum_{\text{pixels}} \sum_{\text{pixels}} R(x, y) \times S(x - \text{R.A.}, y - \text{decl.}),
\]

where \( R \) is a reference epoch map, which we choose to be the first epoch from each region, \( S \) is a succeeding science epoch map to be aligned, and both maps have identical dimensions. The CC of a reference epoch to a science epoch is the measure of how similar the two maps are as a function of the displacement of the science map relative to the reference map. If the two maps were identical and there were zero offset, then the measure of the CC would be an autocorrelation, where the peak max (cor(R.A., decl.)) resides at (R.A., decl.) = (0, 0). The measured radial offset between the reference map and the science map is

\[
\text{Radial offset} = \sqrt{(\Delta \text{R.A.})^2 + (\Delta \text{decl.})^2},
\]

where \( \Delta \text{R.A.} \) and \( \Delta \text{decl.} \) are the angular offsets between max (cor(R.A., decl.)) and (R.A., decl.) = (0, 0) in the right ascension and declination.

To determine the position of max (cor(R.A., decl.)), a nonlinear least-squares regression is used to fit a 2D Gaussian to the inner 5 × 5 px² area, equivalent to a 15″ beam at 850 μm (Dempsey et al. 2013) surrounding the most correlated pixel (e.g., Figure 13). The uncertainty in the measured radial offset is estimated as the uncertainty of the 2D Gaussian fit.
considers a flux-limited sample, where it uses a list of bright, compact small-scale structures, for which there could only be a few in some cases (e.g., IC 348). Comparatively, the cross-correlation method takes into consideration the entire map, including fainter and complex structures possibly missed by GAUSSCLUMPS.

Positional offsets are measured for a total of 51 science epochs over all eight regions, and the median offset is \( \sim 0.6 \) arcsec. Consistent with the initial position offsets measured from GAUSSCLUMPS (see Figure 14). Subsequently, each science epoch is re-reduced with makemap, taking into account the derived offset relative to its reference map. Then, the same correlation and fitting method as described above is applied to the original data to the aligned maps in order to deduce any residual pointing uncertainty.

Using the GAUSSCLUMPS method, we find comparable offset distributions for the unaligned maps. In Figure 14, we compare the right ascension and declination offsets derived using the cross-correlation method with those derived using GAUSSCLUMPS (GC) in a manner similar to Figure 11 and find them to be consistent. The median residual offset after alignment using the GAUSSCLUMPS method is \( \sim 0.03 \) arcsec. Comparatively, the CC method is able to self-consistently align maps to a scale \( \sim 20 \) times finer than the GAUSSCLUMPS method with median residual offsets after alignment of \( \sim 0.03 \) arcsec. This alignment is \( \sim 100 \) times better aligned than the telescope’s pointing error.

Although the median residual offset is \( 0.03 \) arcsec, the accuracy of the alignment is limited by the uncertainty in the residual offset, which is typically larger than \( 0.04 \) arcsec (see Figure 15). The
uncertainty in the residual offset is limited by the uncertainty in the 2D Gaussian fit to the CC, which is a result of the large spread of the CC product (see Figure 13). Therefore, this image alignment method is limited to a single iteration of the CC method, as it will not improve on itself with succeeding iterations.

There do not seem to be any strong correlations between the measured residual offset and the maximum cross-correlation iterations. There are no biases due to the fitting algorithm (see Figure 15). We find that the more bright and compact the small-scale structure that resides within a region, the larger the peak CC value. While using GAUSSCLUMPS, the data in the 2D Gaussian fitting algorithm do not show a strong correlation. Sources embedded within small-scale structure, whereas the CC method does not show a strong correlation toward small-scale or irregular structures. As the survey matures, we will be exploring this alternate technique and refining our methodology to further improve our alignment calibration.

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