Assessing and Improving Low SNR Calibration Solutions in Narrow-Bandwidth ALMA Spectral Windows

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1 Summary

Perhaps as many as 40% of cycle 1 ALMA observations may be collected with one or more very narrow (100 MHz or less) spectral windows (SPWs). For these narrow spectral windows, the signal to noise reached in the calibration observations can often be lower than desirable, reducing the effectiveness of calibrations.

We propose and apply a heuristic to associate narrow spectral windows with wider spectral windows, and use it to examine the phase calibration solutions obtained in pipeline reductions of 82 ALMA executions drawn from 17 NA projects. Test datasets are shown in § 2. The empirical properties of the phase calibration solutions for wide and narrow SPWs are summarized in § 3.2. Key properties seen are:

- The root mean square (RMS) of the individual integration (INT) phase calibration solutions provides a good metric of the solution quality; better, for instance, than the fraction of failed solutions or the RMS of scan-by-scan (INF) solutions.
- The RMS of phase solutions for broad ($\sim 2\,\mathrm{GHz}$) spectral windows is almost always considerably lower (by a factor of 5 or more) than the RMS of phase solutions for the narrow spectral windows in the same executions. This is true for both INT and INF solutions. These data suggest that for narrow ($< 300\,\mathrm{MHz}$) spectral windows, *thermal noise* is almost always the dominant source of variation in the phase solutions (not real, correctible systematic effects).

Note: statements above pertaining to phase solutions, and all such statements in this report, pertain to the *residuals to the WVR phase corrections.*

We implement a simple strategy to calibrate the narrow-band, low SNR SPWs in the manaul data reduction scripts. We apply this strategy to 11 datasets reduced with the manual scripts; two of these datasets are "control" datasets with no *a priori* evident low SNR issues, and two turn out to be problematic for other reasons. For the 7 remaining narrow-bandwidth datasets, one shows consistent phasecal flux densities between the wide and narrow bands both with and without the spectral window mapped calibration. The other 6 all show better results— i.e. narrow band phase cal flux densities more consistent with those measured in the wide bands— when the SPW-mapped calibration procedure is used. Two of these 6 still show significant discrepancies (20% - 30%), indicating that further progress is needed.

Finally, we provide a list of further action items needed.

Summary recommendation for data reduction: For band 7 and longer wavelength, if SPWs narrower than 300 MHz are present, associate with a wider SPW per the heuristic in § 3.1, and implement the data reduction procedure described in § 4. This will result in SPW-mapped reductions for *all* narrow SPWs. For frequencies higher than band 7, the same procedure could be adopted but our analysis has too little narrow-SPW data for these bands to argue for its effectiveness. Further study is needed.

2 Test Datasets

Our primary dataset for empirically characterizing the calibration quality comprises 82 cycle 1 ALMA executions which had narrow spectral windows (SPWs) and pipeline reductions at the NAASC. These datasets are tabulated in Table 1.

Project	Execution	Project	Execution
2012.1.00001	X127	2012.1.00394	X15d
2012.1.00001	X668	2012.1.00394	X5c9
2012.1.00001	X18e	2012.1.00422	X1280
2012.1.00001	X1d4	2012.1.00422	X15e4
2012.1.00031	X13c0	2012.1.00422	Xeeb
2012.1.00129	Xc66	2012.1.00496	X15fc
2012.1.00129	Xfab	2012.1.00554	X3529
2012.1.00129	Xc8b	2012.1.00554	X3af3
2012.1.00178	X14fc	2012.1.00554	X112c
2012.1.00178	X6ca	2012.1.00554	X6ff
2012.1.00178	X123f	2012.1.00554	X88b
2012.1.00178	X12ad	2012.1.00554	Xe44
2012.1.00178	X1603	2012.1.00554	X913
2012.1.00178	X385	2012.1.00554	X14df
2012.1.00178	Xc0	2012.1.00554	X1585
2012.1.00178	X92b	2012.1.00554	X44e
2012.1.00178	X14de	2012.1.00554	X66f
2012.1.00178	X17ed	2012.1.00554	X5c8
2012.1.00178	X1553	2012.1.00554	Xaa4
2012.1.00178	Xc42	2012.1.00554	X493
2012.1.00178	X10d4	2012.1.00554	X66b
2012.1.00229	Xd0a	2012.1.00554	X2be
2012.1.00346	X4324	2012.1.00554	X4c7
2012.1.00368	X1da8	2012.1.00554	X6c6
2012.1.00368	X1246	2012.1.00554	X2d2
2012.1.00368	X31	2012.1.00554	X2ade
2012.1.00368	X43b	2012.1.00603	X6fc
2012.1.00368	X4577	2012.1.00603	X8b4
2012.1.00368	X11d7	2012.1.00683	X5fd
2012.1.00368	Xcfe	2012.1.00688	X1e66
2012.1.00382	X118b	2012.1.00720	X1b1e
2012.1.00382	Xc97	2012.1.00720	X1c87
2012.1.00382	Xea4	2012.1.00720	X2d4
2012.1.00394	X1f3	2012.1.00720	X465
2012.1.00394	X456	2012.1.00720	X79
2012.1.00394	X69e	2012.1.00979	X25a
2012.1.00394	X158e	2012.1.01069	X2730
2012.1.00394	X1188	2012.1.01069	X31aa
2012.1.00394	X3d9	2012.1.01069	X10e9
2012.1.00394	X95e	2012.1.01069	X15b4
2012.1.00394	Xe23	2012.1.01069	Xd54

Table 1: List of pipeline-reduced projects and executions examined.

3 Observed Properties of the Test Data

3.1 Associating Narrow SPWs with Wider SPWs

In general optimally associating narrow SPWs with broader SPWs requires information or assumptions about the observing setup, which can vary. We find that for these test datasets the following heuristic does a good job at associating narrow SPWs with broader SPWs in the same EB:

1. Make a list of the SPW bandwidths, BW.
2. Store the maximum of these bandwidths in a variable named BWMAX = max(individual SPW BWs).
3. For each SPW with BW < 300 MHz
    (a) look for SPWs with BW $> 0.8 \times BWMAX$, which also have $BW >$ the BW of the particular narrow SPW in question (this avoids referencing for the case that all SPWs have the same, narrow bandwidth).
    (b) of SPWs meeting these criteria, choose the SPW whose band center (frequency or wavelength) is closest to the center (frequency or wavelength) of the narrow SPW in question.

In our test datasets there were 190 EB-SPW's with less than 300 MHz bandwidth. 175 of these were successfully associated with broader SPWs by this heuristic; the remaining instances were collected in a mode with only narrow SPWs. The median ratio of wide SPW bandwidth to narrow SPW bandwidth for the set of successfully reference SPWs was 31.2 (mean = 24.4).

3.2 Observed Properties of the Calibration Solutions

In order to assess the quality of calibration solutions, we looked at two quantities: first, the fraction of complex gain calibration solutions flagged as *bad* by CASA; second, the RMS of the phases obtained in the successful solutions. Analysis was confined to the solutions obtained on the phase calibrator, assumed to be the highest source with the highest source ID. Both the INT (individual integration) and INF (scan by scan) solutions from all pipeline reductions in § 2 were examined. A python script was develoepd which extracts the flagged (bad) fraction and RMS phase solution for each execution, spectral window, and solution interval (INT or INF) of a given pipeline reduction.

As noted previously, the WVR-determined phases have already been taken out, so the phases obtained in the antenna based phase gaincal could more properly be called the *phase residuals* to the WVR phase calibration.

The fraction of flagged INT solutions is shown as a function of the RMS of INT phase solutions in Figure 1. Only narrow, successfully mapped SPWs are shown (see § 3.1 for the SPW "mapping" procedure). There are numerous cases where the RMS INT phase is very high ($> 40^\circ$) but the flagging fraction quite low ($< 10\%$). Additionally there are other, legitimate reasons why the flagging fraction may vary that are unrelated to SNR. The flagging fraction is therefore not a very robust diagnostic of SNR.

The phase solutions have contributions from both real, potentially calibratable antenna-based phase variations, and from noise in the determination of the solutions. Due to their shorter integration times, and due to the expected correlation structure of the atmospheric phases (phases should better correlate on short time scales), the RMS of INT solutions are *a priori* expected to provide a better diagnostic of SNR than the RMS of INF solutions. The distribution of RMS phase of INT and INF solutions are shown in Figure 2 and 3, respectively. Wide and narrow bands are broken down separately.

Indeed we find that the RMS of INT solutions provides the most robust diagnostic of low-quality phase solutions[1]. The INF solutions provide a considerably inferior diagnostic: because the phases can sometimes wrap within a single scan, they can average down within a scan and leading the RMS of INF solutions to drastically underestimate the true level of phase stability. There are numerous instances, for example, where the INT RMS is $> 60^\circ$ while the INF RMS is $< 20^\circ$. This can be seen in Figure 4.

As noted in § 3.1 the median ratio of bandwidth in the wide SPW to that in its associated narrow SPW is 31.2 (mean = 24.4). For the case that the narrow band solutions are completely thermal noise dominated— *i.e.*, that the real phase fluctuations you seek to calibrate away are negligible in comparison— this gives an

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[1] One caveat is that if the flagging fraction is high (or complete) the RMS of solutions for a given SPW in a given EB does not exist.

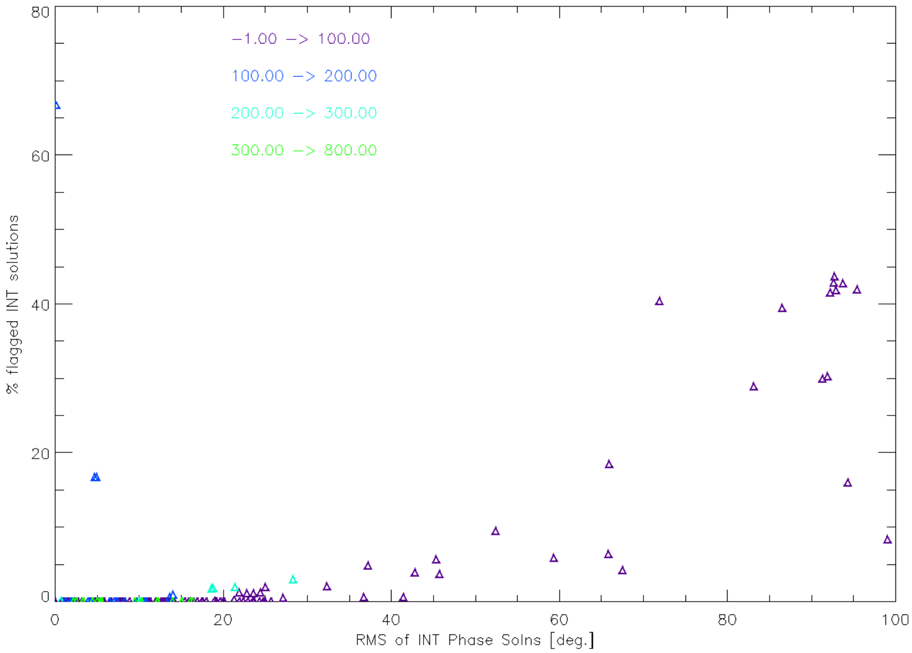

Figure 1: Fraction of INT phase solutions flagged as bad vs RMS of INT solution phases themselves. Both quantities are computed over one entire execution for one SPW. Color encodes the SPW bandwidth in MHz.

expected reduction in the RMS phase of solutions of ~ 5. In fact the observed RMS of phase solutions is very close to this: the median ratio of pre- to post- referencing RMS phase is 5.43 (mean = 3.62) for the INT solutions; and 4.00 for the INF solutions (mean = 2.98). The RMS of the phase solutions is also strikingly low: almost all of the INT phase RMS's over a project are below $< 10°$, and almost all INF phase RMS's over an execution are $< 4°$. As a point of reference, 10° RMS phase corresponds to $\sim 1.5\%$ loss of coherence, *i.e.*, a 1.5% bias low in source amplitudes (valid only in the small-angle limit).

The consistent and substantial reduction in the RMS of the INT phase solutions for broad SPWs compared to narrow SPWs suggests two things: i) the narrow SPW solutions are *almost always* measuring mostly thermal noise; ii) the default procedure for narrow SPWs should be to derive the phase calibration from wider SPWs.

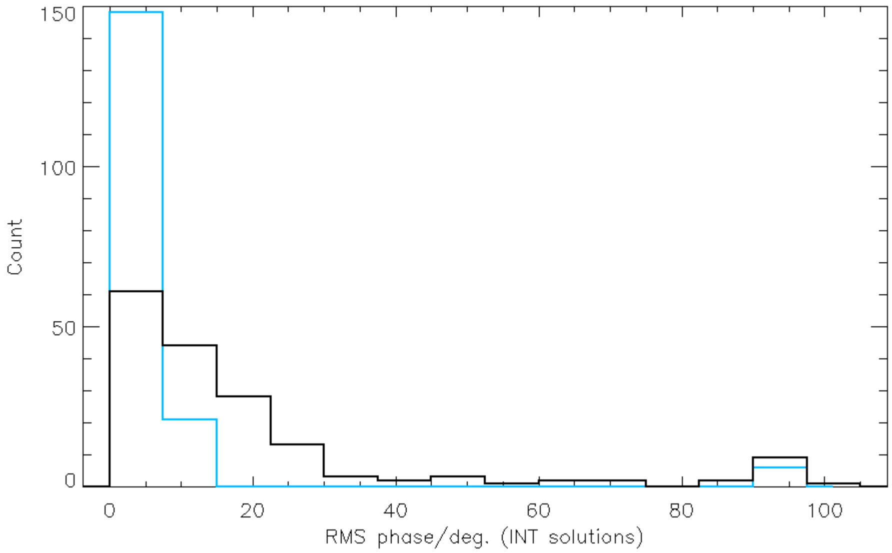

Figure 2: Distribution of RMS of INT phase solutions for narrow SPWs (black), and for the wider SPWs that were associated with them (cyan). As before, RMS's are computed over the entire execution for a single SPW.

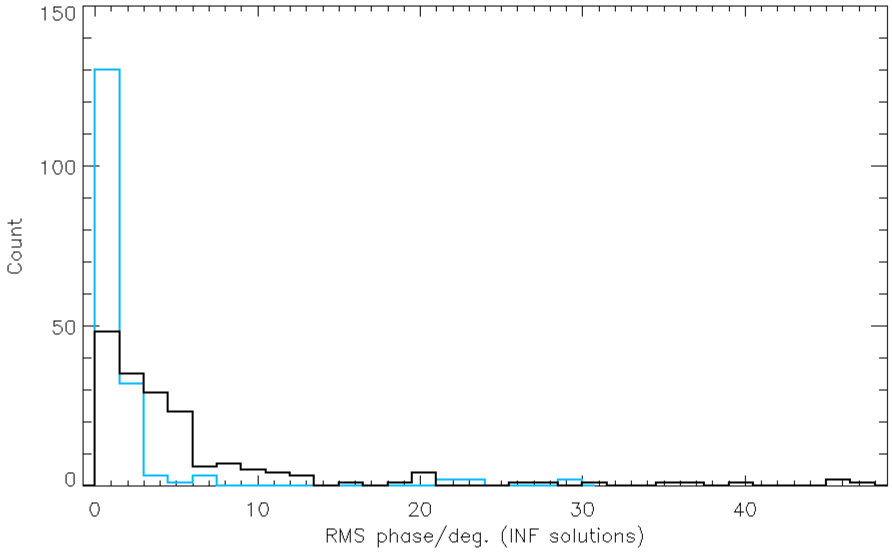

Figure 3: Same as Fig. 2 but for the INF solutions: distribution of RMS of INF phase solutions for narrow SPWs (black), and for the wider SPWs that were associated with them (cyan). RMS's are computed over the entire execution for a single SPW.

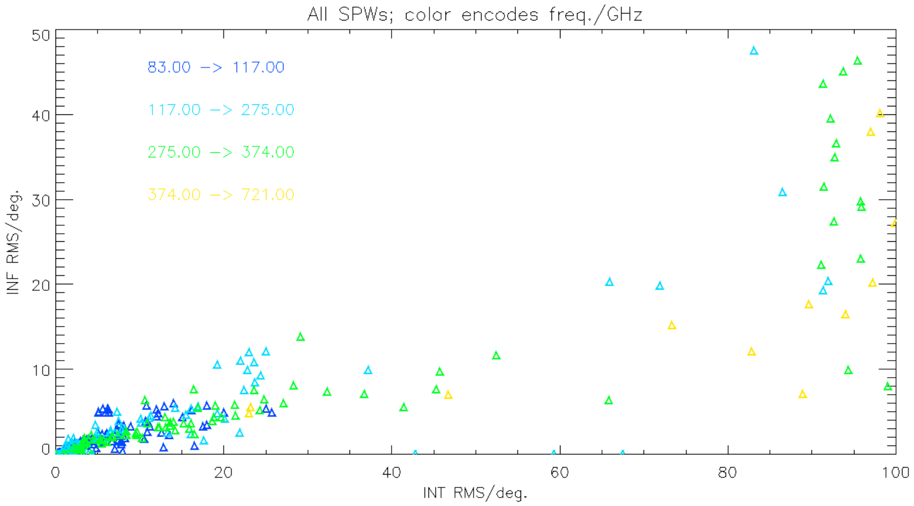

Figure 4: RMS of whole-scan phasecal solutions (INF) vs. RMS of integration by integration phasecal solutions (INT). All SPWs are included in this plot, not only narrow ones. Note that in the absence of phase-wrapping within the INF (scan) interval, thermal noise will typically reduce the INF phase RMS by a factor of 3 or less relative to the INT phase.

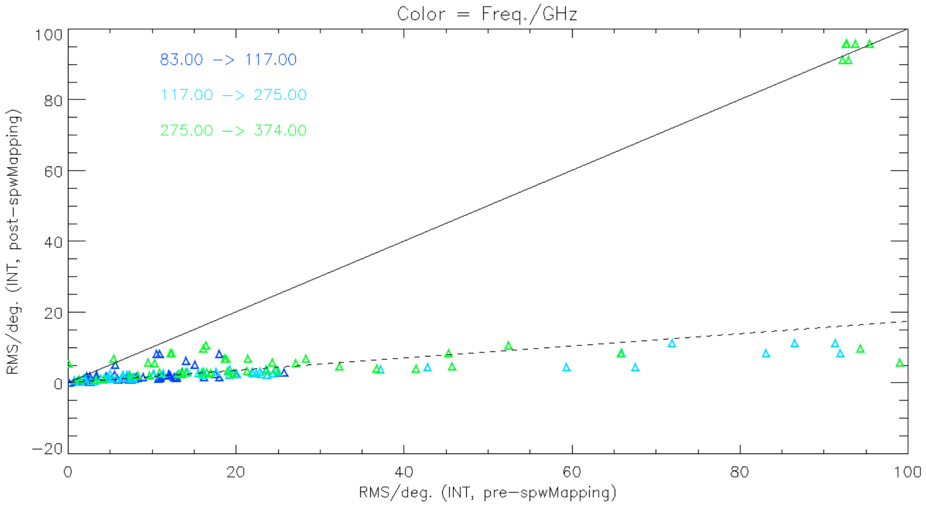

Figure 5: Direct comparison of narrow SPW INT phase RMS (x-axis) with the post-referencing phase RMS (y-axis). The dashed line shows the expected improvement for the case that the noise in the phase solutions is purely thermal noise, and the bandwidth ratio is 2000/60 (for an improvement of $\sqrt{2000/60} = 5.77$ in SNR). Here color encodes the frequency of the SPW center in GHz. The high-RMS outlier not improved by SPW mapping is project 129, execution Xc8b (band 7).

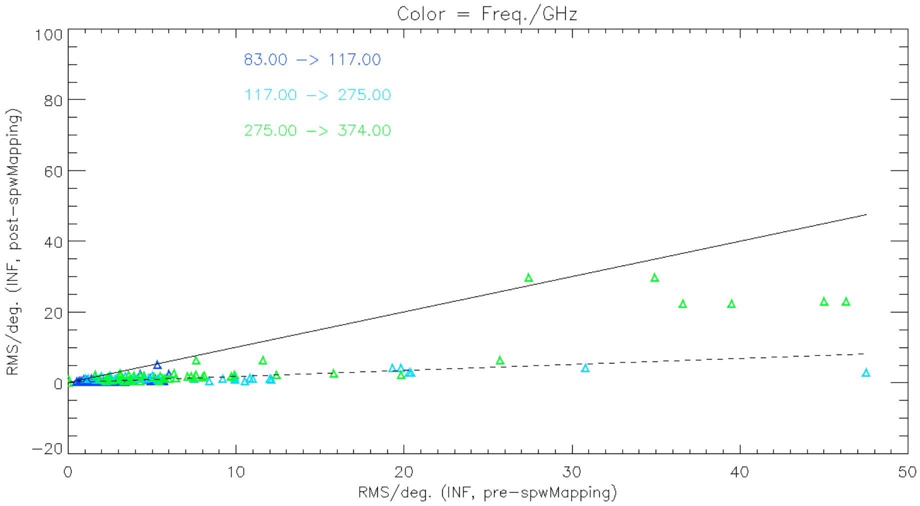

Figure 6: Same as Fig. 5, but for the INF solutions.

4 Calibration Procedure

A simple procedure to deal with low SNR SPWs is as follows:

1. After deriving the bandpass calibration, at the beginning of gain calibration, derive a new “phase-up” table by doing a phase cal on the bandpass calibrator. This has the effect of removing SPW to SPW phase offsets by referencing all subsequent phase corrections to zero. Apply this table in all subsequent gaincal and applycal statements.
2. Define spectral window referencing maps (SPWmaps) that will map the narrow SPWs into wide SPW. Use these SPWmaps in all subsequent gaincal and applycal steps.

This is illustrated in the following excerpt from a manual pipeline reduction script:

```
# Gain calibration
mystep = 15
if(mystep in thesteps):
  casalog.post('Step '+str(mystep)+' '+step_title[mystep],'INFO')
  print 'Step ', mystep, step_title[mystep]

  # In this example, SPW 2 is a narrow band that we want
  #  to reference to the wider SPW 3.
  # The first two spw "maps" are needed for argument
  #  syntax reasons in some of the gaincal() and applycal() statements
  #  later.
  spwmap_phaseup  = [0,1,2,3]
  spwmap_bandpass = [0,1,2,3]
  spwmap_phaseint = [0,1,3,3]
  spwmap_phaseinf = [0,1,3,3]
  spwmap_fluxinf  = [0,1,3,3]

  # This is the new "phase-up" table-
  os.system('rm -rf 229_spwmap.ms.split.phase_up')
  gaincal(vis = '229_spwmap.ms.split',
    caltable = '229_spwmap.ms.split.phase_up',
    field = '0', # J0522-3627
    solint = 'inf',
    refant = 'DV22',
    gaintype = 'G',
    calmode = 'p',
    gaintable = '229_spwmap.ms.split.bandpass')

  # supply the phase-up table here and all subsequent-
  os.system('rm -rf 229_spwmap.ms.split.phase_int')
  gaincal(vis = '229_spwmap.ms.split',
    caltable = '229_spwmap.ms.split.phase_int',
    field = '0~2', # J0006-0623,J2232+117,J2323-0317
    solint = 'int',
    refant = 'DV22',
    gaintype = 'G',
    calmode = 'p',
    gaintable = ['229_spwmap.ms.split.bandpass', '229_spwmap.ms.split.phase_up'])

  os.system('rm -rf 229_spwmap.ms.split.ampli_inf')
  gaincal(vis = '229_spwmap.ms.split',
    caltable = '229_spwmap.ms.split.ampli_inf',
    field = '0~2', # J0006-0623,J2232+117,J2323-0317
    solint = 'inf',
    refant = 'DV22',
    gaintype = 'T',
    calmode = 'ap',
    spwmap = [spwmap_bandpass,spwmap_phaseup,spwmap_phaseint],
    gaintable = ['229_spwmap.ms.split.bandpass', '229_spwmap.ms.split.phase_up', '229_spwmap.ms.split.phase_int'])


...


# Application of the bandpass and gain cal tables
```

```
mystep = 17
if(mystep in thesteps):
  casalog.post('Step '+str(mystep)+' '+step_title[mystep],'INFO')
  print 'Step ', mystep, step_title[mystep]

  for i in ['0', '1']: # J0006-0623,J2232+117
    applycal(vis = '229_spwmap.ms.split',
      field = i,
      gaintable = ['229_spwmap.ms.split.bandpass', '229_spwmap.ms.split.phase_up', '229_spwmap.ms.split.phase_int', '229_spwmap.
      gainfield = ['', '', i, i],
      spwmap = [spwmap_bandpass, spwmap_phaseup, spwmap_phaseint, spwmap_fluxinf],
      interp = 'linear,linear',
      calwt = F,
      flagbackup = F)

  applycal(vis = '229_spwmap.ms.split',
    field = '2,3', # BP_Psc
    gaintable = ['229_spwmap.ms.split.bandpass', '229_spwmap.ms.split.phase_up', '229_spwmap.ms.split.phase_inf', '229_spwmap.ms
    gainfield = ['', '', '2', '2'], # J0541-0541
    spwmap = [spwmap_bandpass, spwmap_phaseup, spwmap_phaseinf, spwmap_fluxinf],
    interp = 'linear,linear',
    calwt = F,
    flagbackup = F)
```

The full script can be found attached to
`https://safe.nrao.edu/wiki/bin/view/ALMA/LowSnrNarrowBandReduction`

5 Detailed Reduction

We re-reduced 11 datasets using the manual reduction scripts, modified to implement the procedures described in § 3.1 and § 4. These datasets are summarized in Table 2. SPW referencing was performed for all narrow windows.

Proj.	EB	Ant.	Rx	Notes
683	X311	7m	B3	
422	Xeeb	7m	B9	
129	Xc66	12m	B6	phasecal too faint for broad SPW (SNR=3)
394	X5e5	12m	B3	
1069	Xfe	7m	B6	
229	X429	12m	B7	ID'd as potentially bad from flagging fractions
178	Xc42	7m	B6	fluxcal referenced to narrow window (Titan)
178	X10d4	7m	B6	fluxcal referenced to narrow window (Titan)
178	X14de	7m	B6	
683	X38	12m	B3	control
554	X14df	12m	B6	control

Table 2: Test datasets for spectral window referencing.

Of the 11 datasets, two were control datasets with narrow spectral windows but no problems evident *a priori*, e.g., from phase RMS's or flux ratios. Two of the EBs had other problems which grossly corrupted the calibrations: 129:Xc66 had very faint phase calibrator, evenin the widest SPW; and 178:Xc42 had an indeterminate problem resulting in a factor of $\sim 100\times$ error in the phasecal fluxes for the *wide* SPWs. This may be related to the fact that the narrow windows were automatically used for flux calibration due to the presence of a spectral line on the flux calibrator (Titan). There was another case (178:X10d4) of flux referencing which does not appear to have been problematic.

To evaluate the datasets we consider the ratio of the average flux density of the phase calibrator obtained in the narrow window(s) to that obtained in the wide window(s). For the control datasets, flux densities were negligibly changed. Results for non-problematic, non-control datasets are summarized in Table 3. Of these 7 narrow-band datasets, one actually showed consistent results for the narrow bands *without* SPW mapping, in spite of having been identified as likely having low SNR from the flagging fractions. The remaining 6 narrow-band datasets all show better results— i.e. narrow band flux densities more consistent with those measured in the wide bands— when the SPW-mapped calibration procedure is used. Two of these 6 still show significant discrepancies (20% - 30%), indicating that further progress is needed.

For a couple of these executions the phase calibrators were also imaged and their positions compared with and without SPW mapping. No position shifts were found. This should be done systematically with check sources or science sources, not phasecals. The low RMS phases suggest that at least for the bands considered here, the positions are not likely to change significantly.

Proj.	EB	BW_{min}	INF RMS	INT RMS	$S_{pre,narrow}/S_{wide}$	$S_{post,narrow}/S_{wide}$
683	X311	100 MHz	24°	NaN	2.79	1.30
422	Xeeb	938 MHz	8°	80°	1.34	0.99
394	X5e5	58 MHz	11°	25°	1.45	1.22
1069	Xfe	62 MHz	0°	1°	1.70	1.05
229	X429	468 MHz	2.0°	5.8°	0.99	0.99
178	X10d4	62 MHz	12°	80°	1.87	1.06
178	X14de	62 MHz	12°	90°	1.73	1.08

Table 3: Results from SPW-mapped reduction comparison (non-problem, non-control datasets). BW_{min} is the bandwidth of the narrowest SPW. Also shown are representative INF and INT phase solution RMS numbers for the narrow band(s); and the ratio of phasecal flux density in the narrow SPW(s) to that in the wide SPW(s), before SPW mapping; and the same quantity after SPW mapping the calibration of the narrow bands to the wide bands.

These reductions are located on the CV cluster at
`/lustre/naasc/nbrunett/narrow_band/`
and
`/lustre/naasc/sschnee/Functional/pipeline/LowSN/`

6 Follow-up Actions/Future Work

1. Check images of "check sources" or science targets with SPW mapping applied — verify that positions do not shift significantly. (NAASC - extend this analysis)
2. Write simple python script to do the SPW association described in § 3.1 (Brian or Remy)
3. Understand why SPW mapping the flux calibrator worked in one case (178:X10d4) and didn't in another (178:Xc42). See if there is a simple workaround in data reduction.
4. Why are the phasecal flux densities for 683:X311 and 394:X5e5 still 20% - 30% high for the narrow windows?
5. Follow up individual anomalies seen in data: e.g., project 129:Xc8b high RMS not fixed by spwMapping; why does 1069:Xfe have a *zero* INF phase RMS?
6. Investigate dependence on baseline length — intrinsic phase stability is likely to be worse on longer baselines.
7. Investigate adequacy of SNR for INT gain solutions for the wide SPWs.
8. Look at higher frequency data: the data examined here were almost all Band 7 or lower frequency. Intrinsic stability of the residual phases will likely be worse at higher frequency.
9. Avoid placing wide SPWs on lines in primary flux calibrator, and/or avoid using flux calibrators with lines (P2G/JAO).