Phase RMS investigation on the datasets calibrated with combine='spw'

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Summary: For low SNR data calibration, often combine='spw' is used to increase SNR of the phase calibrator. In this calibration heuristics, the important assumption is that the phase offset between spws are constant or at least very stable during the observation. Then combining spw will boost SNR and decrease the phase RMS of the phase calibrator, which will be applied for correcting the phase variation in science scans. We investigate how this assumption is reliable and the combine='spw' produces the phase solution following the expectation from the statistics of SNR in the measurement set.

Background: ALMA (C4 patch) pipeline acceptance testing in December 2016 & January 2017 produced, through a complicated series of events, a pair of strangely discrepant reductions of the same "benchmark" dataset (2016.1.01400.S, MOUS uid A001/X88f/X250) in which one of two reductions triggered the calibration pipeline "low-SNR/combine=SPW" heuristics and the other did not. This presumably happened because of an update to the flux density information of the source in question in the database between the two pipeline runs. What was anomalous & concerning was that the run *with* the low-SNR heuristic produced a notably lower quality result (higher background noise in the image of the phasecal). Detailed investigation showed that the problem was due to phase instability over time between SPWs within a single antenna (DV03) such as rendered invalid the basic assumption of the low-SNR/combine=SPW heuristic. ***Since stability of SPW-to-SPW phases over the duration of an execution is currently assumed by calibration techniques when needed (low SNR) -- and is intrinsically assumed without in-production verifiability for the non-standard Bandwidth Switching observing method -- we undertook a systematic investigation of how widespread similar phase problems might be.*** The initial investigation of 2016.1.01400.S also showed that two antennas (DA42, DA50) had poor positions, but that this problem was not related to the DV03 phase issue. The DV03 phase issue was reported on PRTSPR-24865.

Datasets**:** Six MOUS were selected from among the datasets reported in the "NA PL Review Summary" spreadsheet () that had a recent pipeline run triggering the combine='spw' heuristic. The total number of ASDM (execution blocks) processed in this test is 12. The executions occurred over the period 15 June 2016 to 4 Jan 2017. For the majority of the processings used here, the reference antennas were DA41 or DA49; note that these are *not* the antennas which have recently idenitfied position errors (DA42: erroneous over 1/3/17-2/17; DA50: erroneous over 12/27/16 - 2/17) -- although as noted below there is one execution from August 2016 where it appears DA41 could potentially have a bad position.

Method: For each ASDM, we split the phase calibrator and made clean images. Recall that the phase calibrator data had already been (complex gain) calibrated using combine='SPW'. Then gaincal task was executed to solve for the phase solution of each spw, with solint='inf'; ***if the assumption of relative SPW phase stability is valid, these solutions should all have zero***

phase up to thermal noise. Expected thermal noise is in the range of 0.1deg to a few deg RMS for most aggregate SPWs. We investigate the variation of these phase solutions in each spw using mean and RMS of the phase. In the following plots, we shows the distribution of the mean and RMS (de-meaned) of the antenna base phase solution.

Results:

a) In 12 executions over six MOUS's ***ten of the executions had 'phase outliers' > +/-15 deg in at least one spw***, and ***4 of them had 'phase outliers' > +/-45 deg***. By "phase outlier" we mean "one or more antennas with *mean* phases in at least one SPW (from the self-cal solution, after application of the combine='SPW' phase solutions) of absolute value greater than 15 degrees."

b) The most notable SPW-phase outlying antennas were ***DV03*** (seven executions) and ***DV07*** (four executions). Other affected antennas are ***DV21***, ***DA58***, ***DV10***, ***DA46***, ***DA54***, ***DA41, DA50, DA51, DA54, & DA55*** (one execution each). See Table on next page.

b2) The antennas which showed poor SPW-to-SPW phase stability (by this test) within a given execution were generally *not* the same antennas which were outliers in a plot of the phasecal visibilitiies (amps or phases, pre-selfcal). However perhaps there is a weak tendency for the phasecal visibility outliers to implicate the set of antennas identified in this overall analysis.

b3) We checked that the bad-SPW-phase-stability antennas identified in this analysis didn't show signs that would indicate bad antenna positions such as slopey bandpass phases or overall (not differential) phase corrections that "ramp" with sky slews. Except for DA41 none jumped out at us.

c) For one ASDM (X7daa in 2015.1.00847.S_2017_01_12T17_17_06.311) with significantly larger RMS for almost all of antennas, we found that all of bandpass solutions have systematic phase drift in phase vs frequency space. This significantly degraded the phase stability. Original reference antenna was DA41 and changing the reference antenna when executing self-cal does not improve the phase stability. This situation could perhaps be improved by re-calibrating the data using different reference antenna or updating the position of DA41. This execution occurred in 8/2016; another execution in 9/2016 also showed signs of DA41 having a bad position (but it was not the reference antenna in that execution).

d) Finally, we compiled all RMS and SNR of ASDMs and plotted the relation between SNR and phase RMS, which expected to be SNR~1/RMS. The result show that the relation seems to follow the expectation albeit with varying normalization constants, which might be related with the estimate of SNR using flux estimate varying with observing band, calibrator chosen, date of observation, etc.. Indeed the observed phase RMS's in some of these executions was sufficiently low that it seems likely that combine='SPW' was triggered only due to an anomalously low (or absent) flux density estimate (e.g. first 2 executions of project 2015.1.01287).

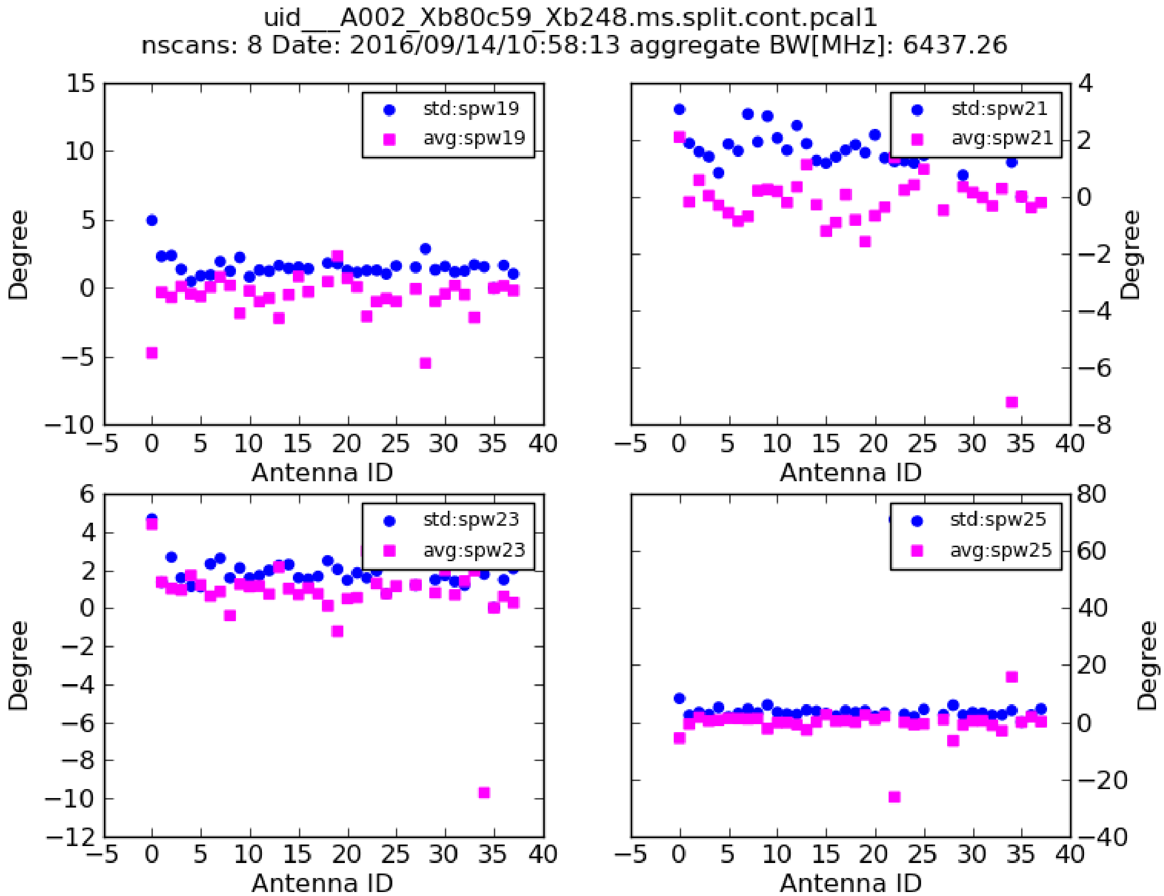
Antenna:	project	execution UID	date Obs	Sci Spws affected
DV07	2015.1.00773	A002/Xb80c59/Xb248	2016/9/14	25
	2015.1.01287	A002/Xb4655b/X5653	2016/6/17	25
	2016.1.00193	A002/Xbc7c73/X753	2017/1/1	25
	"	A002/Xbc6682/Xb75	2017/1/1	25
DV21	2015.1.00773	A002/Xb80c59/Xb248	2016/9/14	25
DA58	2015.1.00942	A002/Xb66ea7/X9c8f	2016/8/10	25,27
DV10	“	A002/Xb44b49/X8084	2016/6/15	27
DA46	2015.1.01506	A002/Xb5bd46/X4aad	2016/7/23	19,25,27
DA54	"	"	"	“
DA41	2016.1.00193	A002/Xbc6682/Xb75	2017/1/1	25
DA50	2015.1.00847	A002/Xb6d0c2/X7daa	2016/8/17	17,27
DA51	“	"	"	19,25,27
DA54	“	"	"	19,25,27
DA55	"	"	"	19,25,27

Table of identified Antenna SPW-to-SPW phase deviations

1. 2015.1.00773.S_2017_01_18T22_29_38.913 (Band 6)

spw 19,21,23 (TDM), 25 (FDM)

Plot of phaseINF vs time for phasecal on this execution suggests DA41 may have a bad position.



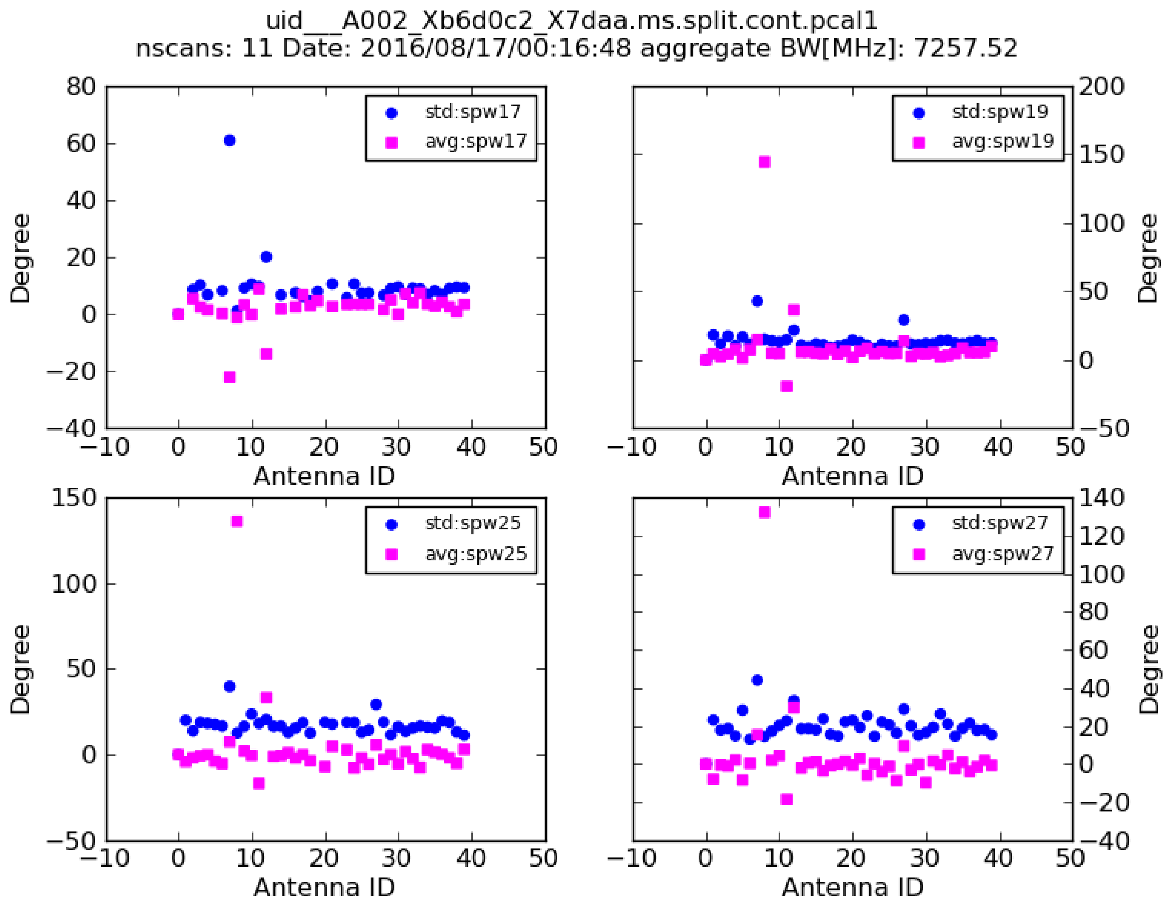
Mean phase outlier: {spw25: DV07,DV21}

SNR of the phase calibrator
{spw19: 20.5, spw21: 18.6, spw23: 16.26, spw25 9.58}

Phasecal pre-self-cal visibility amplitude outliers:{}
(No significant amplitude outliers in this EB)

2. 2015.1.00847.S_2017_01_12T17_17_06.311 (Band 8)

spw 17,19 (TDM), 25,27 (FDM)

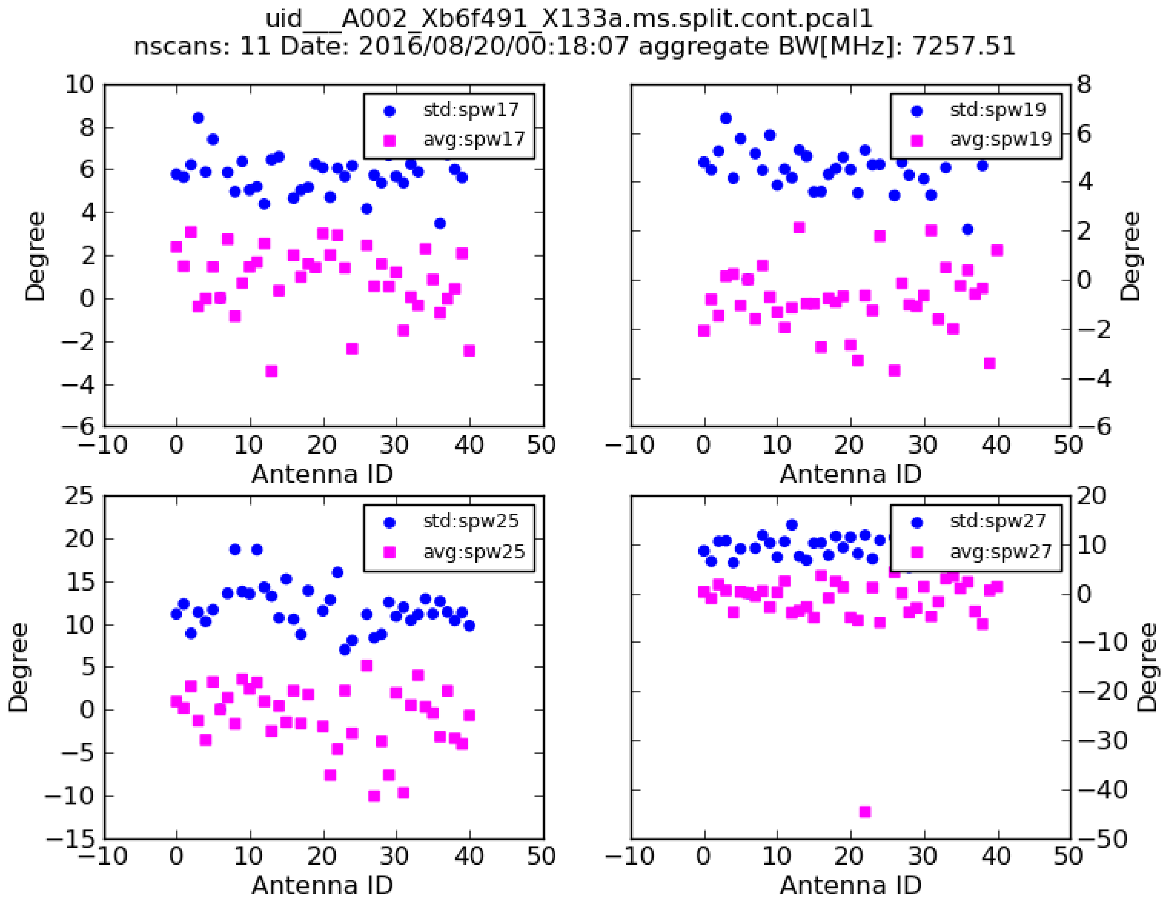


Mean phase outlier: {spw17:DA50},{spw19:DA51,DA54,DA55},
{spw25:DA51,DA54,DA55},{spw27:DA50,DA51,DA54,DA55}

SNR of the phase calibrator
{spw17: 11.4, spw19: 12.8, spw25: 7.7, spw27: 8.8}

This ASDM has systematic phase drift in bandpass solution, potentially due to a bad position for the reference antenna (DA41). Changing reference antenna (e.g. DA49, DV20, DV22,DV18) when doing self-cal does not improve the situation and the outlier antennas identified here are still the ones with phase outliers.

Phasecal pre-self-cal visibility amplitude outliers:{spw17:DA41&&DA51, DA43&&DA50, DA54&&DA55}*(Per-baseline amplitude outliers in this EB. Possibly related to reference antenna?)*



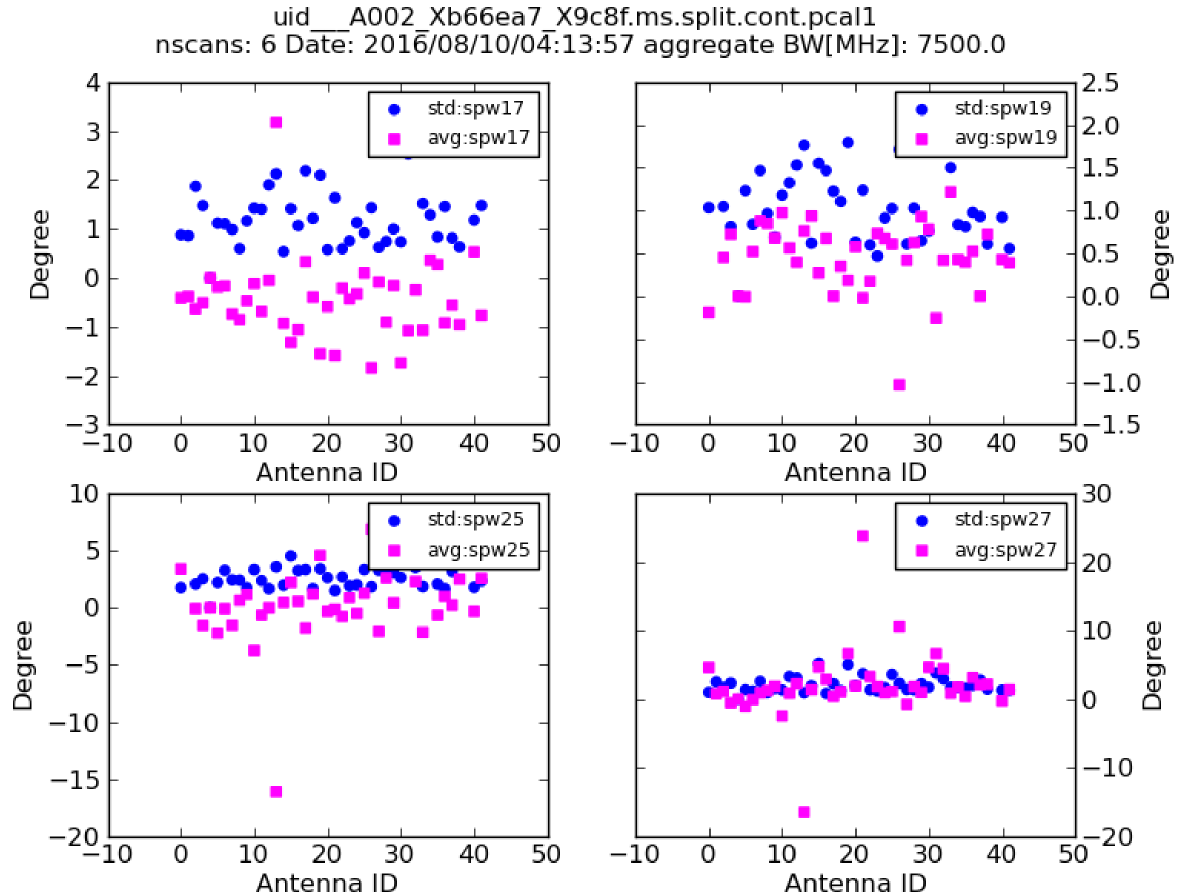
Mean phase outlier:{spw27:DV03}

SNR of the phase calibrator
{spw17: 12.5, spw19: 13.9, spw25: 9.2, spw27: 10.2}

Phasecal pre-self-cal visibility amplitude outliers:{}
(No significant amplitude outliers in this EB)

3. 2015.1.00942.S_2017_01_04T16_57_10.700 (Band 8)

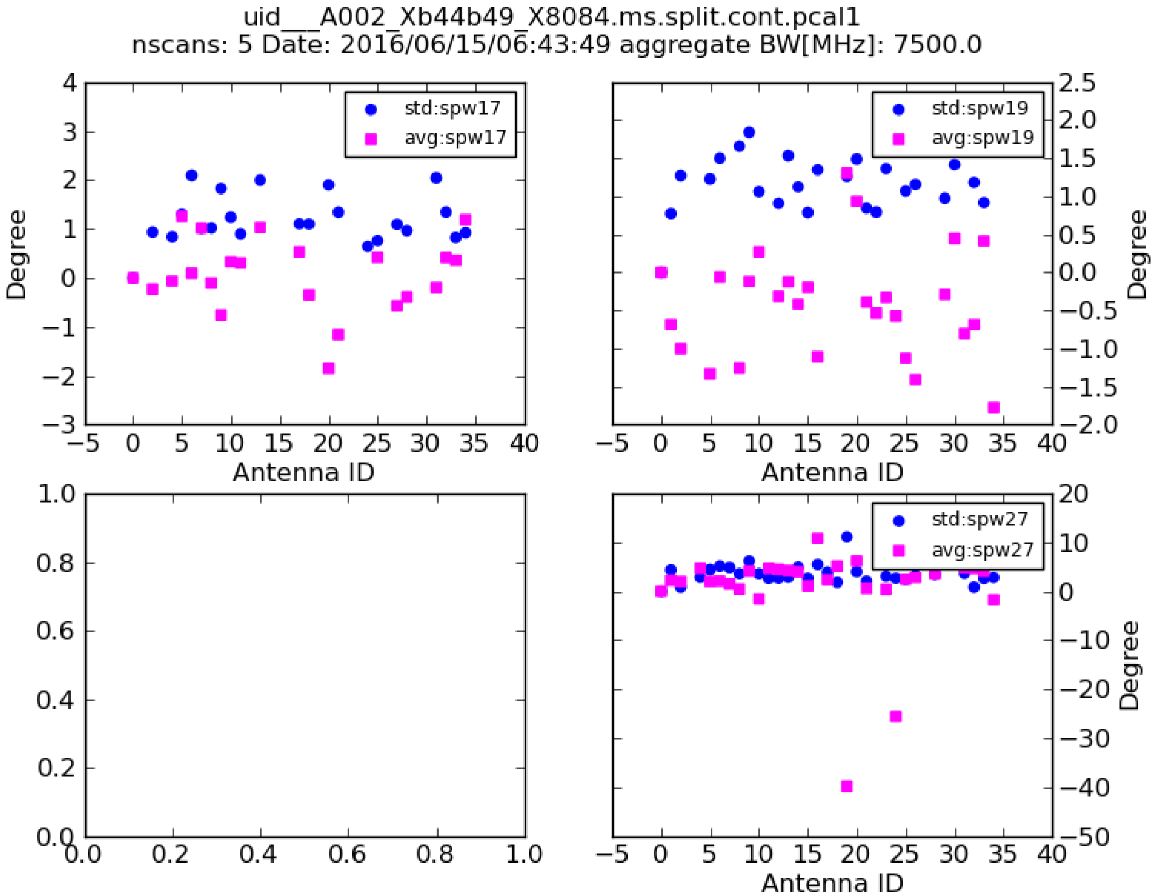
spw 17,19 (TDM), 25,27 (FDM)



Mean phase outlier:{spw25:DA58},{spw27:DA58,DV03}

SNR of the phase calibrator
{spw17: 65.5, spw19: 68.9, spw25: 24.2, spw27: 47.4}

Phasecal pre-self-cal visibility amplitude outliers:{spw19:DA43},{spw25:DA43}
(does not seem related to the antennas with phase outliers)



Mean phase outlier: {spw27:DV03,DV10}

SNR of the phase calibrator
{spw17: 51.3, spw19: 53.0, spw25: 8.72, spw27: 30.3}

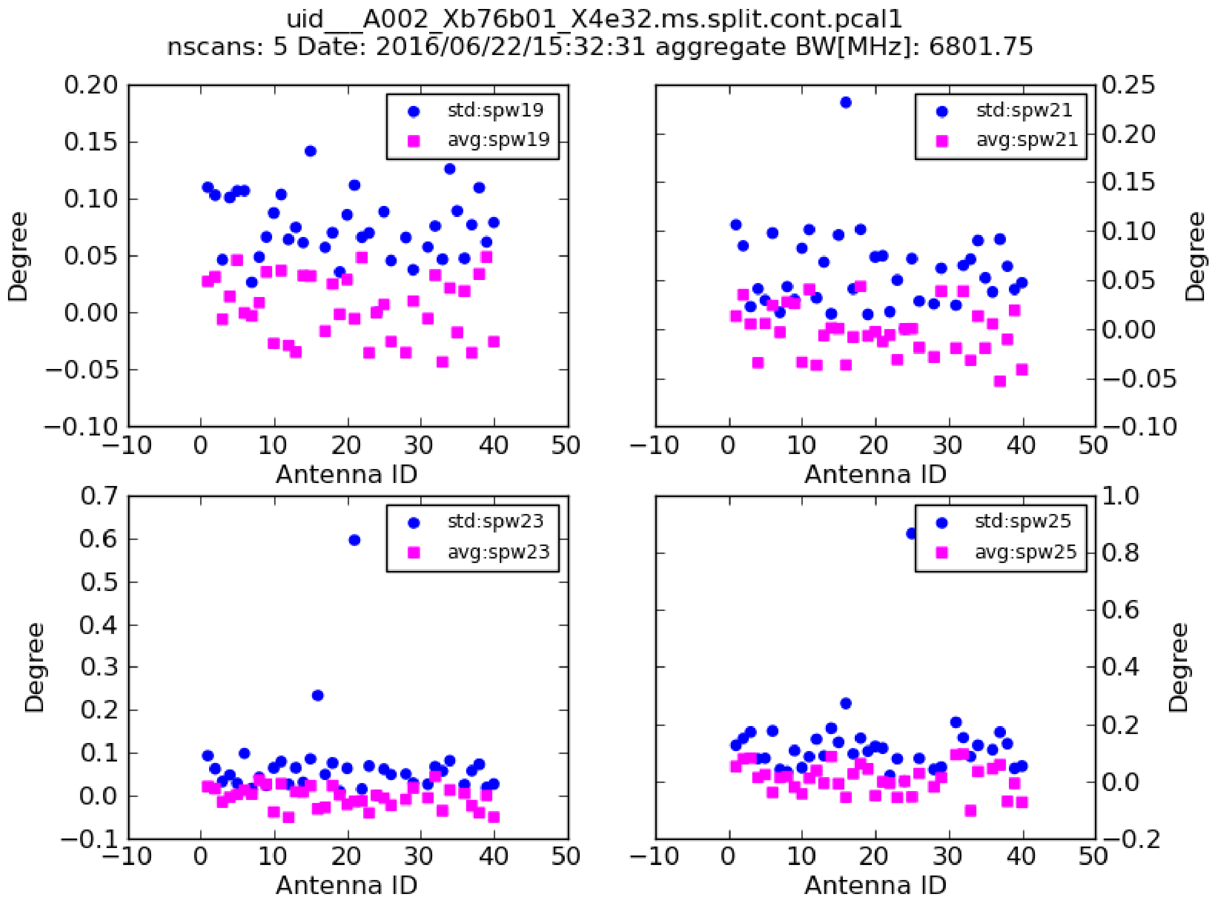
The entire spw25 has been 100% flagged in the calibration due to low SNR in the phase calibrator field, and therefore no phase gain solution has been obtained in this analysis.

Phasecal pre-self-cal visibility amplitude outliers:{}
(No significant Phasecal pre-self-cal visibility amplitude outlierss in this EB)

4. 2015.1.01287.S_2016_11_14T18_45_21.924 (Band 3)

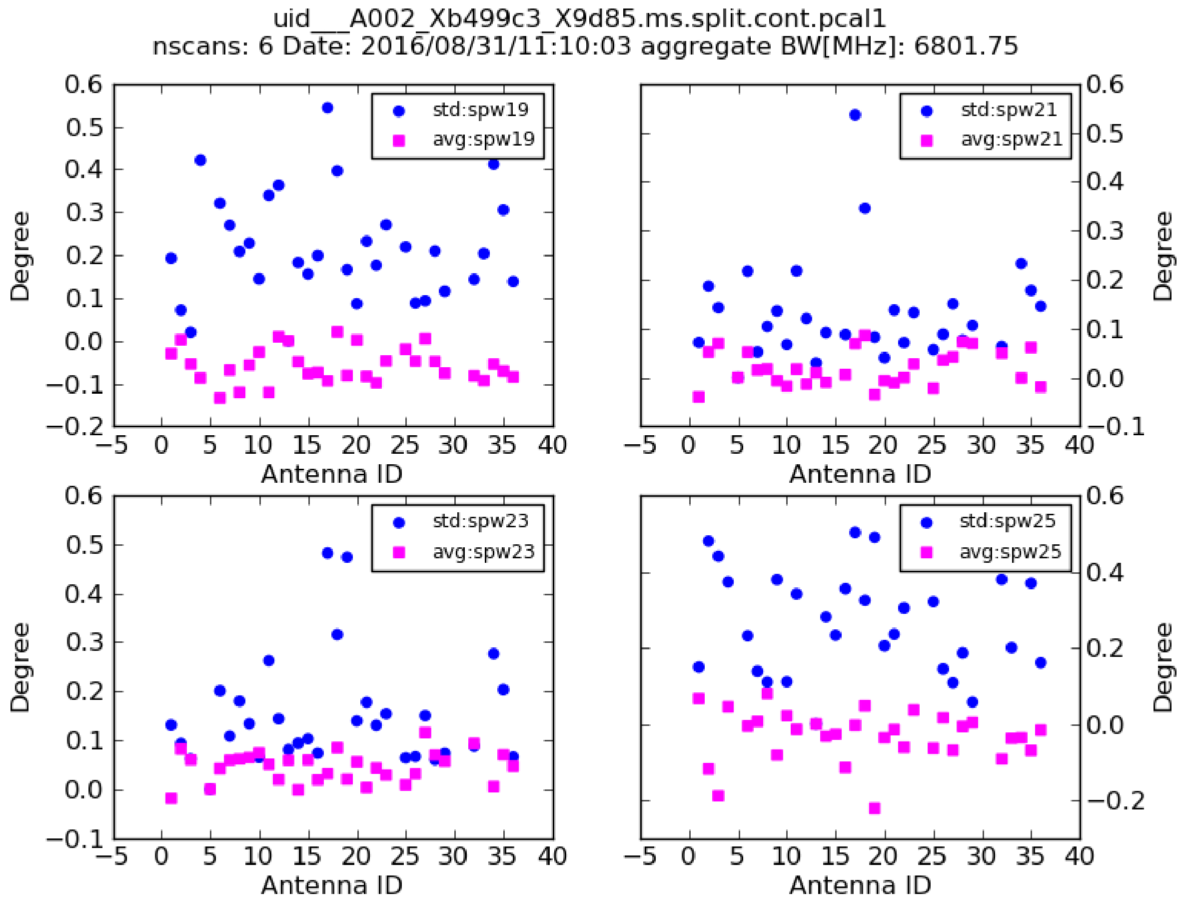
spw 19,21,23 (TDM), 25 (FDM)

For one of these executions (X9d85), the GPCAL.inf table has mulitple SPW solns in it even though the weblog seems to indicate COMBINE=SPW was triggered [????]



SNR of the phase calibrator
{spw19: 31.3, spw21: 54.6, spw23: 53.2, spw25: 15.7}

Phasecal pre-self-cal visibility amplitude outliers:{}
(No significant amplitude outliers in this EB)



SNR of the phase calibrator
{spw19: 63.7, spw21: 101, spw23: 96.6, spw25: 33.1}

Phasecal pre-self-cal visibility amplitude outliers:{spw19:DA41, DA49},{spw21:DA47, DA22},{spw23:DA47, DV17, DV22}
(Per-antenna amplitude outliers in this EB. Does seem related to phase decorrelation, but there are no antennas with phase outliers for this EB...)

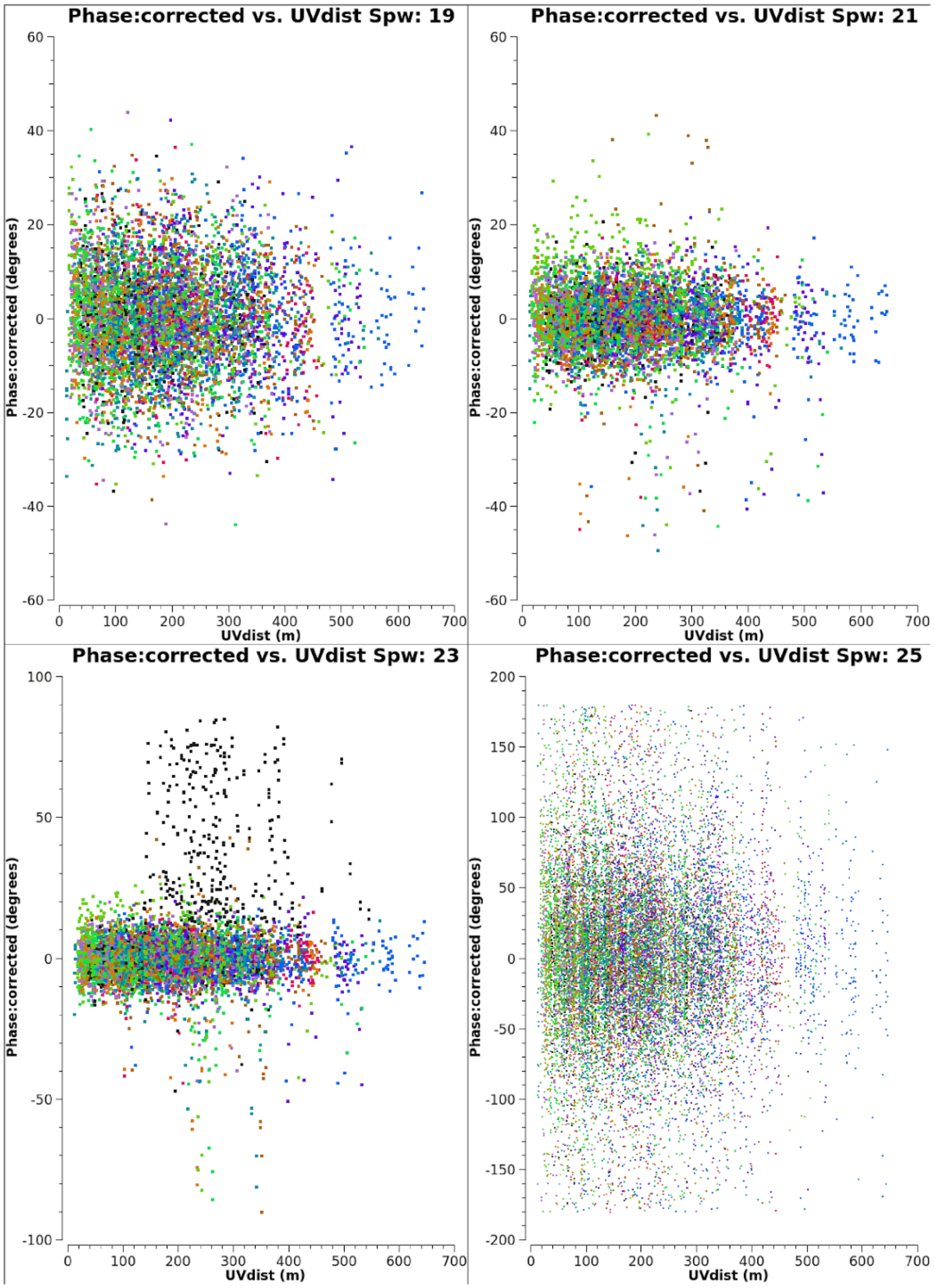
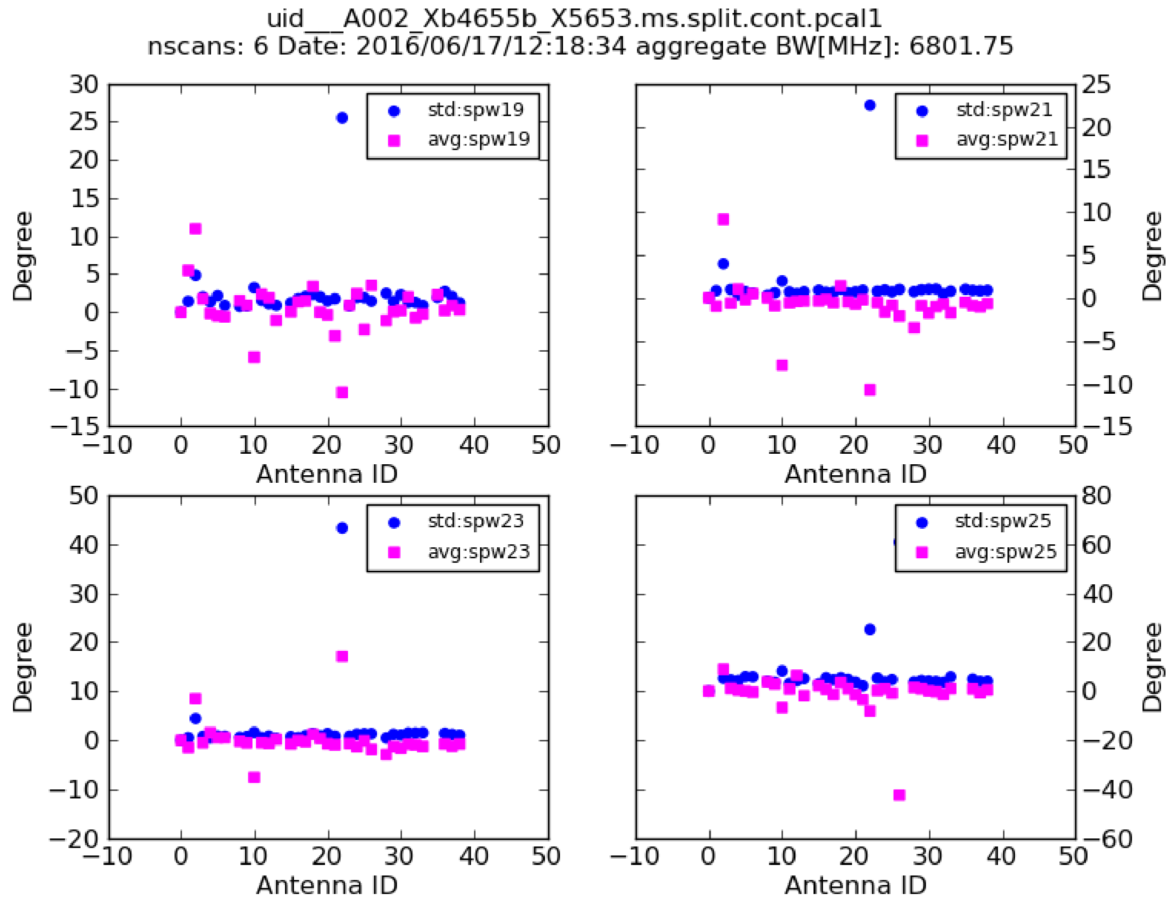


Figure: visibility phase vs uv-distance for phasecal scans (pre-self calibration)



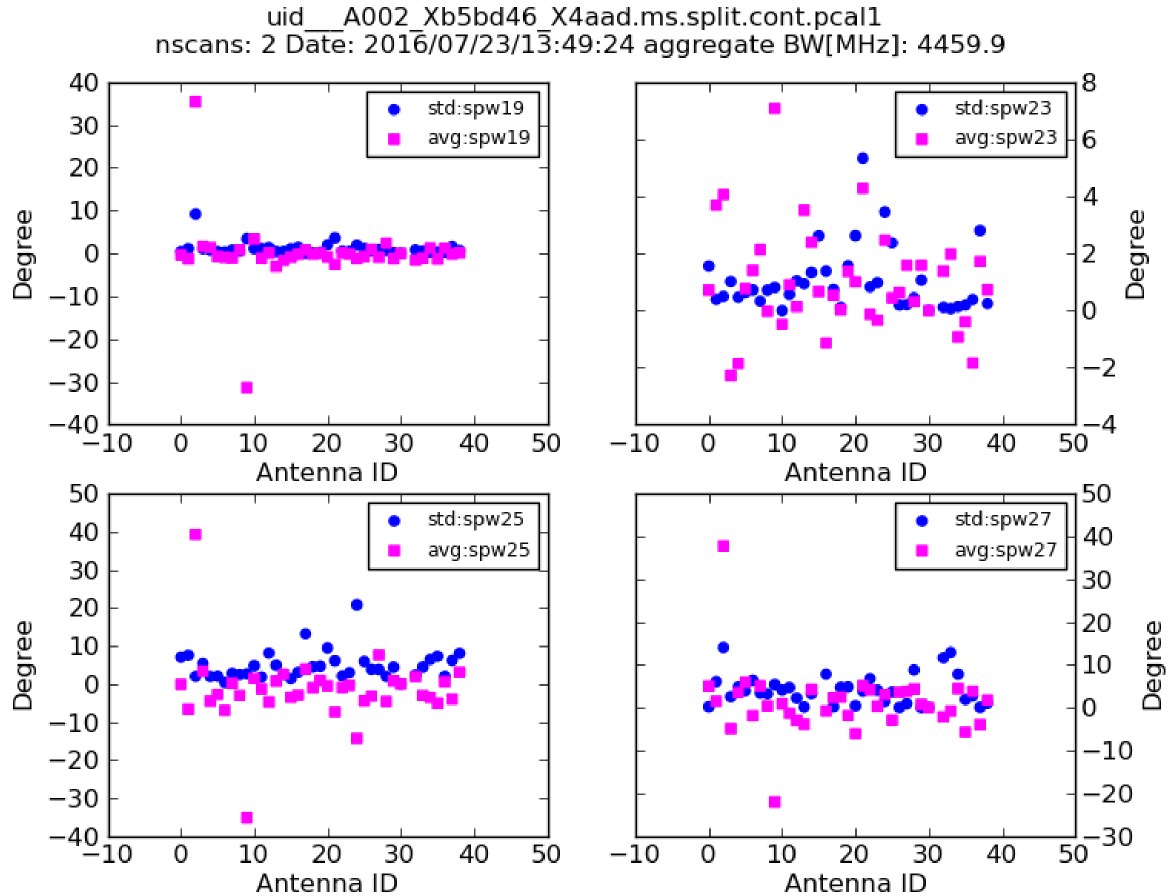
Mean phase outlier: {spw23:DV03},{spw25:DV07}

SNR of the phase calibrator
{spw19: 60.2, spw21: 102.7, spw23: 98.8, spw25: 30.3}

Phasecal pre-self-cal visibility amplitude outliers:{spw23:DA46&&DA54}
(A few per-baseline amplitude outliers in this EB. Does not seem related to antennas with outlier phases.)

5. 2015.1.01506.S_2016_11_30T21_17_58.619 (Band 7)

spw 19,23 (TDM), 25,27 (FDM)

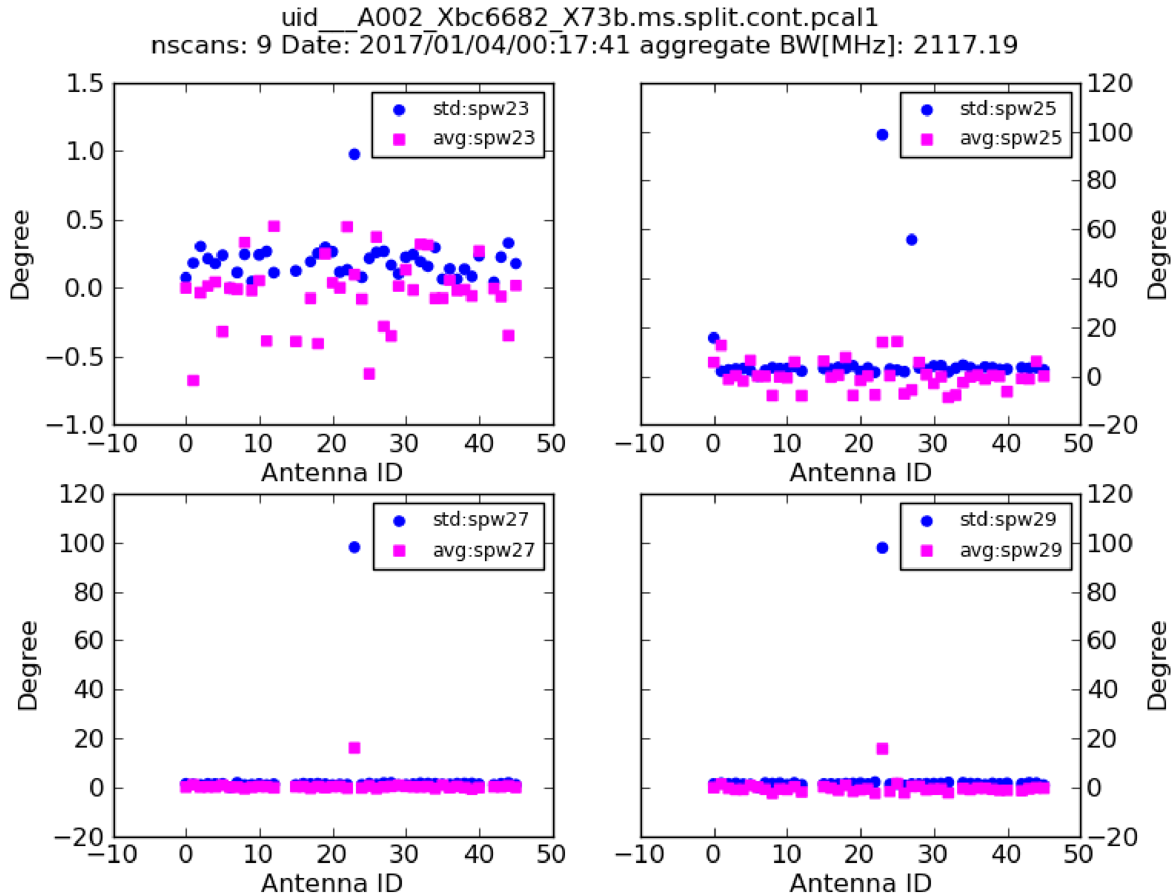


Mean phase outlier:{spw19:DA46,DA54},{spw25:DA46,DA54},{spw27:DA46,DA54}

SNR of the phase calibrator
{spw19: 19.2, spw23: 17.3, spw25: 9.4, spw27: 8.3}

Phasecal pre-self-cal visibility amplitude outliers:{spw23:DA46,DA54}
(A few per-antenna amplitude outliers in this EB. Seems related to phase decorrelation on that spw, but seems inverely related to antennas with outlier phases for this EB) -- note that in this case, the comparison of the pre-self-cal & post-self-cal results suggests SPW23 appears to have a problem that has contaminated the other SPWs.

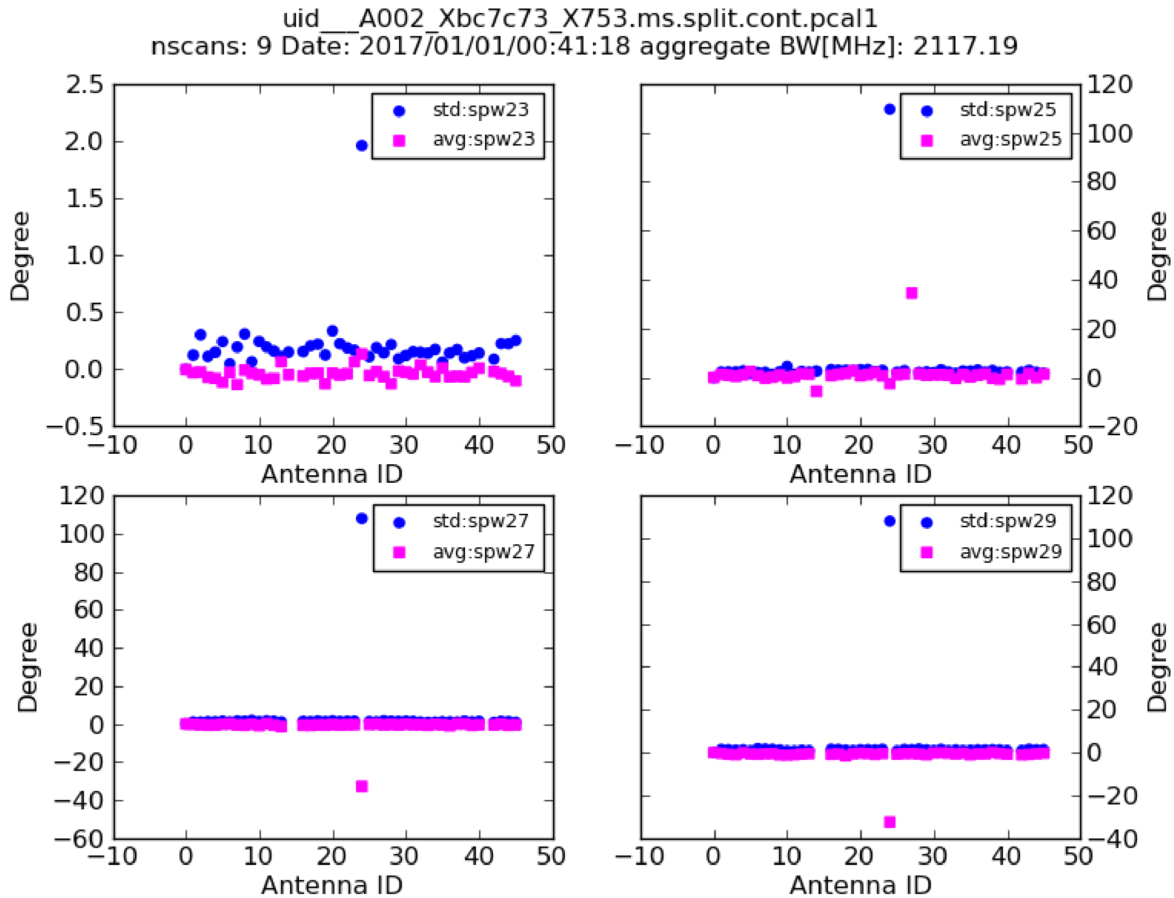
6. 2016.1.00193.S_2017_02_16T22_53_07.151 (Band 3)
spw 23,25,27 (TDM), 29 (FDM)



Mean phase outlier: {spw27:DV03},{spw29:DV03}

SNR of the phase calibrator
{spw23: 161.1, spw25: 27.0, spw27: 55.5, spw29: 52.7}

Phasecal pre-self-cal visibility amplitude outliers:{}
(No significant amplitude outliers in this EB)



Mean phase outlier: {spw25:DV07},{spw27:DV03},{spw29:DV03}
SNR of the phase calibrator
{spw23: 154.0, spw25: 26.0, spw27: 53.0, spw29: 51.0}

Phasecal pre-self-cal visibility amplitude outliers:{spw23:DA59},{spw27:DA58},{spw29:DA58}
(Per-antenna amplitude outliers, apparently also related to phase decorrelation, but unrelated to antennas with phase outliers for this EB.)

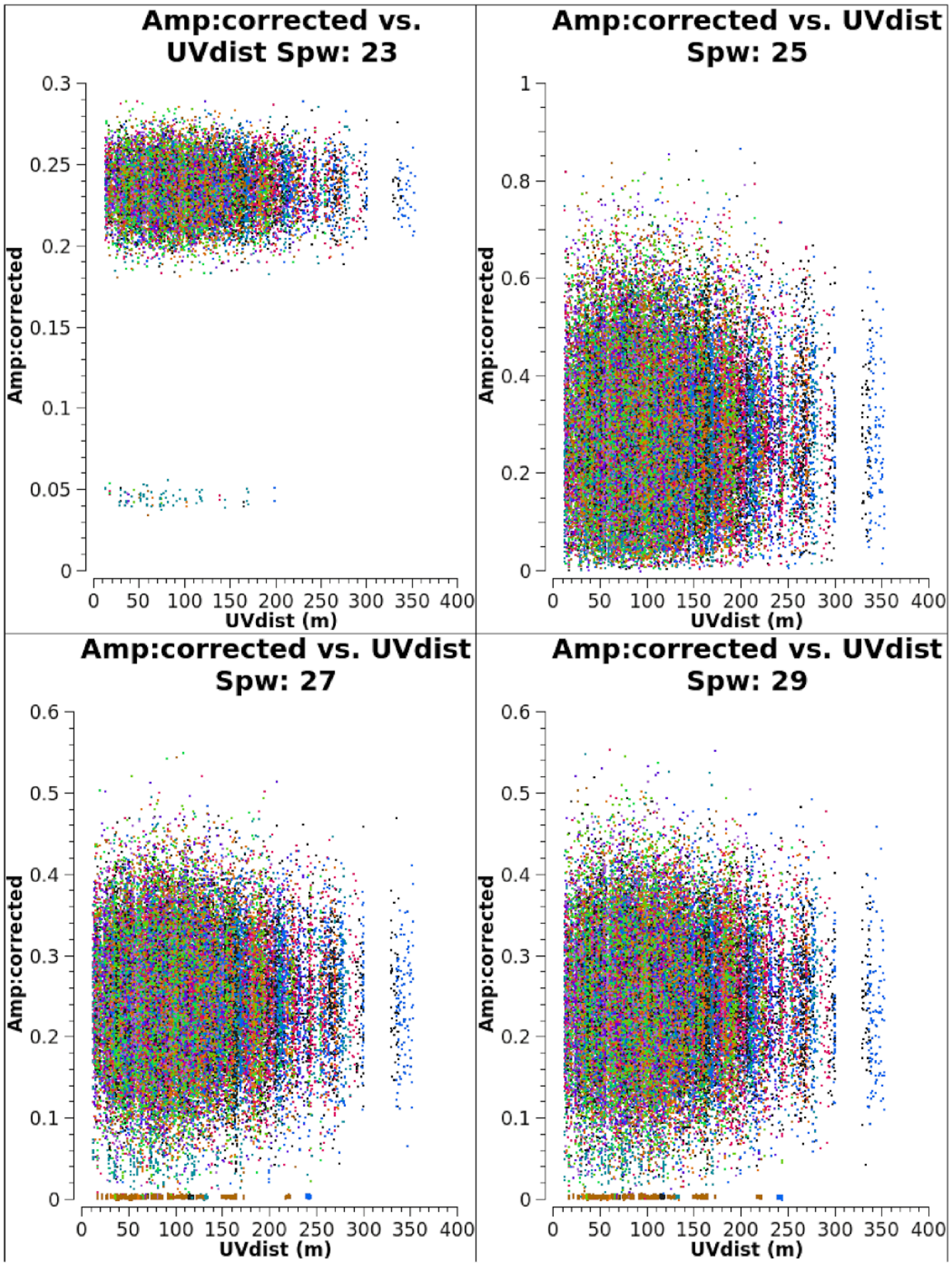


Figure: visibility amplitude vs uv-distance for phasecal scans (pre-self calibration)

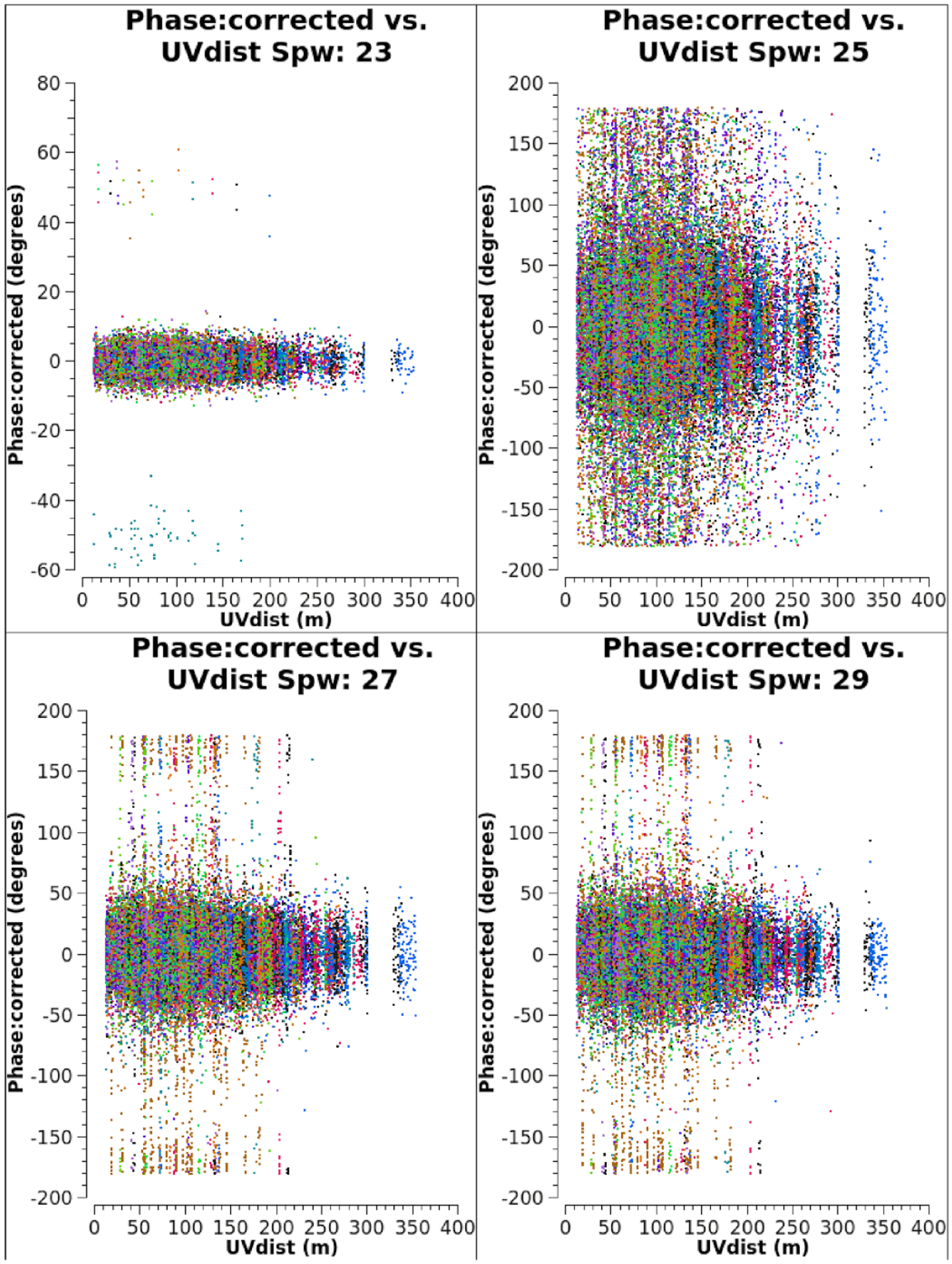
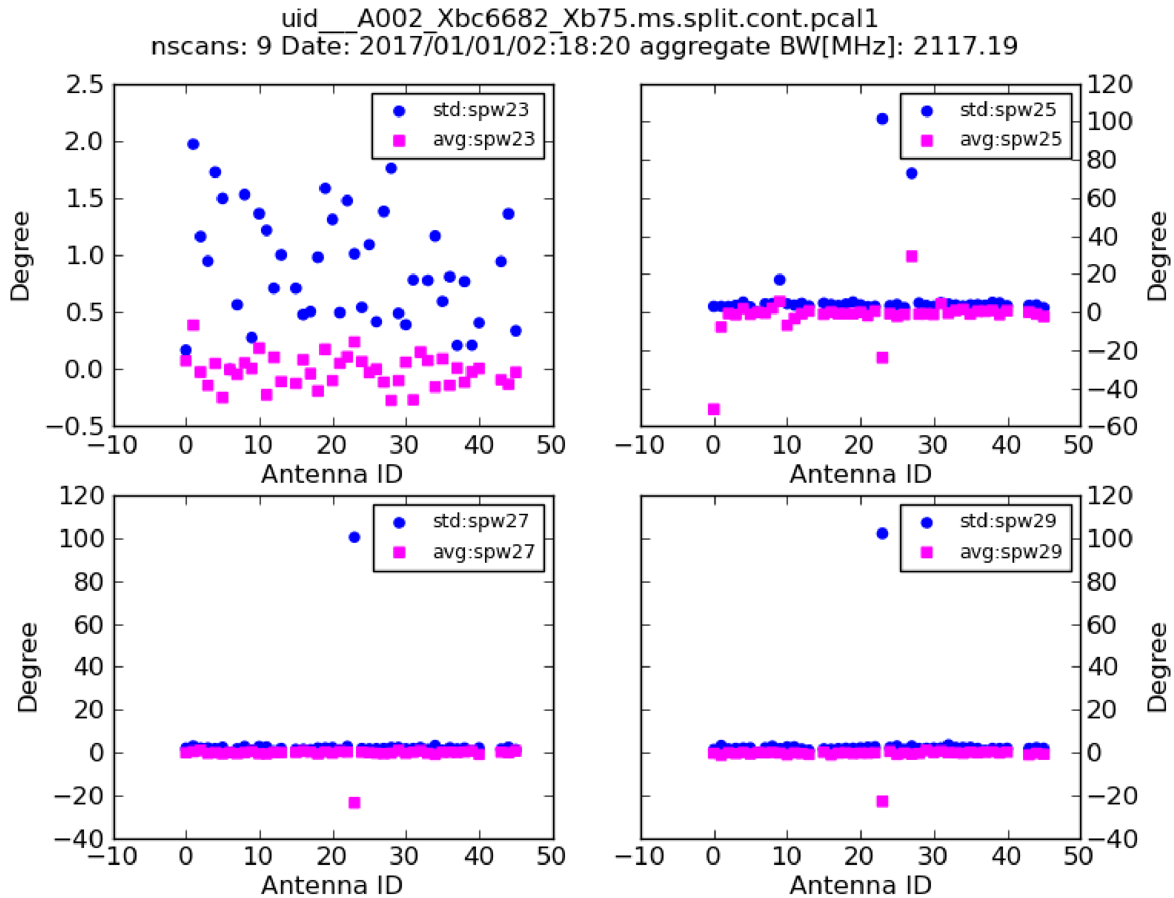
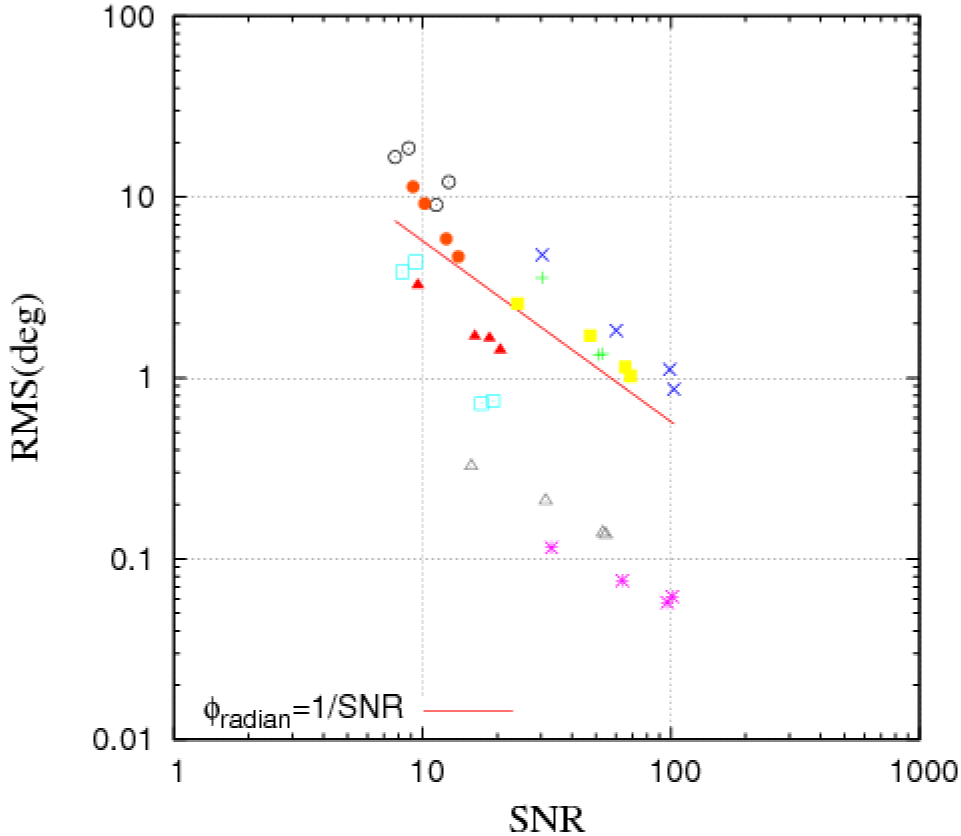


Figure: visibility phase vs uv-distance for phasecal scans (pre-self calibration)



Mean phase outlier: {spw25:DA41,DV03,DV07},{spw27:DV03},{spw29:DV03}
SNR of the phase calibrator
{spw23: 128, spw25: 20.6, spw27: 44.5, spw29: 41.8}

Phasecal pre-self-cal visibility amplitude outliers:{}
(No significant amplitude outliers in this EB)



Colored data points: observed phase solution RMS (of per SPW phase-INF solutions on the phase cal with the combine='SPW' phase solution [and other calibrations] pre-applied) vs au.gaincalsnr() SNR estimate; all calculated and plotted for *each SPW*. Different colors & symbols indicate different executions. ***Red line***: the expected relation between phase RMS in radian and SNR of the visibility (equation (9-17) in Taylor, Carilli and Perley 1999), which is converted into degree. Note that since the plotted phase RMS values are *relative to another phase solution* -- specifically the combine='SPW' one-- the noise is expected to be slightly higher than the "stand-alone" phase noise for that SPW. In essence these solutions are phase differences and the expected phase noise for a given SNR will increase by the quadrature sum of the per-SPW phase noise (which dominates) and the phase noise from the rest of the SPWs considered in aggregate. This small effect is not shown, since it is expected that scatter in the above plot is dominated a) the individual SPW noise; & b) the uncertainty in the phase cal flux density estimates.