VLBA Test Memo #77

Flux Calibration Issues in RDBE DDC-mode Data

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June 28, 2024

Abstract

Late 2020, the MOJAVE team reported a change in the 15GHz (2cm) VLBA flux density scale. Data taken after mid 2019 (∼ June 2019) showed a systematic 10% to 20 % lower flux compared to past MOJAVE data and quasi-simultaneous single dish data taken with the OVRO monitoring program[1] (see https://www.cv.nrao.edu/MOJAVE/, "VLBA Flux Density Scaling Issue"). The data reduction methods remained the same over those years.

Although the MOJAVE team re-reduced their data with the suggested technique for bandpass calibration following the VLBA Sci. Memo #37 (Walker et al. 2014), this resulted in a further 10% flux density reduction compared to their original approach, as well as significant differences in the bandpass solutions. The start date of the flux discrepancy matches a transition from the poly-phase filterbank (PFB) ROACH digital back end (RDBE; Romney et al. 2018) mode (personality) to the digital downconverter (DDC) personality in ∼ August 2019 to facilitate higher data rates.

Initial on-sky tests of the backend seemed to show some decorrelation of the signals in DDC mode in one polarization (LCP) which is handled by RDBE-2. Further investigation in the lab showed intermittent digital signal processing issues with the DDC personality, resulting in aliasing and decorrelation within each subband.

Below, we discuss on-sky and laboratory tests as part of our efforts to identify and resolve the issue as well as calibration strategies to re-reduce archival data being impacted by this systematic flux density shift.

1 On-sky tests

A series of on-sky tests were run (project codes TA035E to TA035R), comparing polarizations, and the DDC and PFB personalities (see Table 1).

Project IDs TA035E (PFB mode) and TA035F (DDC mode) showed a consistent 12% drop in flux densities in DDC mode. TA035EG, TA035EH, TA035I and TA035J repeated these tests at C-band and showed no significant loss in flux density. TA035O and TA035P configured the RDBEs to use the same setup that MOJAVE used in their observations, but swapped which RDBE handled which polarization. This showed the problem remained with RDBE-2 (i.e. did not depend on polarization). Finally TA035Q and TA035R setup the RDBEs to receive the same polarization each. In this case again RDBE-2 showed the issue, independent of whether LCP or RCP was sent to it.

Though the root cause seems to be better understood from the lab tests discussed below (Section 2), why the issue is so much more prevalent in RDBE-2 is still not fully understood.

Figure 1 shows the pattern of signal loss when RDBE-2 is setup to handle LCP in DDC mode. Signal falls off with decreasing frequency, possibly indicating some form of aliasing.

On-sky test observations			
Block ID	Date	Band	Description
TA035E	2021-03-12	KU	PFB mode with four channels overlapping with TA035F
TA035F	2021-03-12	KU	DDC mode
TA035G	2021-04-22	C	PFB mode with four channels overlapping with TA035H
TA035H	2021-04-22	C	DDC mode
TA035I	2021-04-27	C	DDC mode
TA035J	2021-04-27	C	PFB mode with four channels overlapping with TA035I
TA035K	2021-05-19	KU	DDC mode (MOJAVE setup where RCP was handled by RDBE1)
TA035L	2021-05-19	KU	DDC mode (MOJAVE setup where LCP was handled by RDBE1)
TA035M	2021-07-13	KU	repeat of TA035K due to labeling issues
TA035N	2021-07-13	KU	repeat of TA035L due to labeling issues
TA035O	2021-09-04	KU	repeat of TA035M due to data issues
TA035P	2021-09-04	KU	repeat of TA035N due to data issues
TA035Q	2021-10-10	KU	RCP to both RDBEs
TA035R	2021-10-10	KU	LCP to both RDBEs

Table 1: On-sky tests comparing DDC/PFB and the two RDBEs at Ku and C band.

2 Lab tests

The VLBA test rack, located in the Domenici Science Operations Center in Socorro, NM, is outfitted with the same digital back end equipment as the VLBA stations. It was used to run a series of tests using one of the on-sky scripts, minimally modified to run on the test rack (project ID TA035Q). An RF broadband noise source and sinusoidal test tone (724.39 MHz) were mixed. This signal was then split and introduced to the signal inputs of the two RDBE units: vlb-1-dbe-1 and vlb1-dbe-2. The RDBE configuration was identical to the on-the-sky tests, and used DDC mode producing four 32-MHz-wide dual-polarization subbands centered at 672, 704, 736, and 768 MHz. As in the standard setups, each RDBE handles one "polarization" though in these lab tests each unit received a copy of the same locally-generated signal.

Several test data sets were taken and the resulting VDIF data were processed into power spectra and cross-power spectra using either `vdifspec` or `dspsr` (consistent results were obtained with both software packages). From these the normalized correlation coefficient, $C = |RL|/\sqrt{RR * LL}$, can also be computed. Since the same signal was sent to each unit, we in principle expect $C = 1.0$, however quantization effects typically reduce the measured value slightly. The behavior of the system was not consistent from test to test; two examples of typical results are shown in Figure 2. In many examples, no significant problems were seen (e.g., Fig. 2, right panel): The injected tone was found at the expected frequency, and values of $C \sim 0.9$ were seen with no notable spectral structure. Spurious narrowband signals are generally seen at the centers of some subbands; these are previously-known and thought to be inconsequential. However, other scans showed systematic decorrelation as a function of subband ($C < 0.8$, sometimes as low as $\sim$0.6). In these cases, a "mirror image" of the injected tone was also seen, in one polarization only, at a power level $\sim$12 dB lower than the injected signal. No variability as a function of time was observed within each test; the system seems to remain in one state or the other.

Further investigation of the VDIF data taken during these bad states revealed systematic differences between the observed total power levels (or equivalently, state counts) of the even-numbered and odd-numbered samples as a function of time within each subband, typically by a factor of $\sim$40%. This feature was not present during the normal-looking data sets. Effectively it appears that intermittently, a different data scaling is applied to every other sample. This appears to be the cause of the mirror-imaged tone and the decorrelation seen in these data. The magnitude of the effect also seems consistent with the flux density discrepancies observed on the sky. While the effect did not show up consistently in our tests, in the actual

[1] https://www.cv.nrao.edu/MOJAVE/

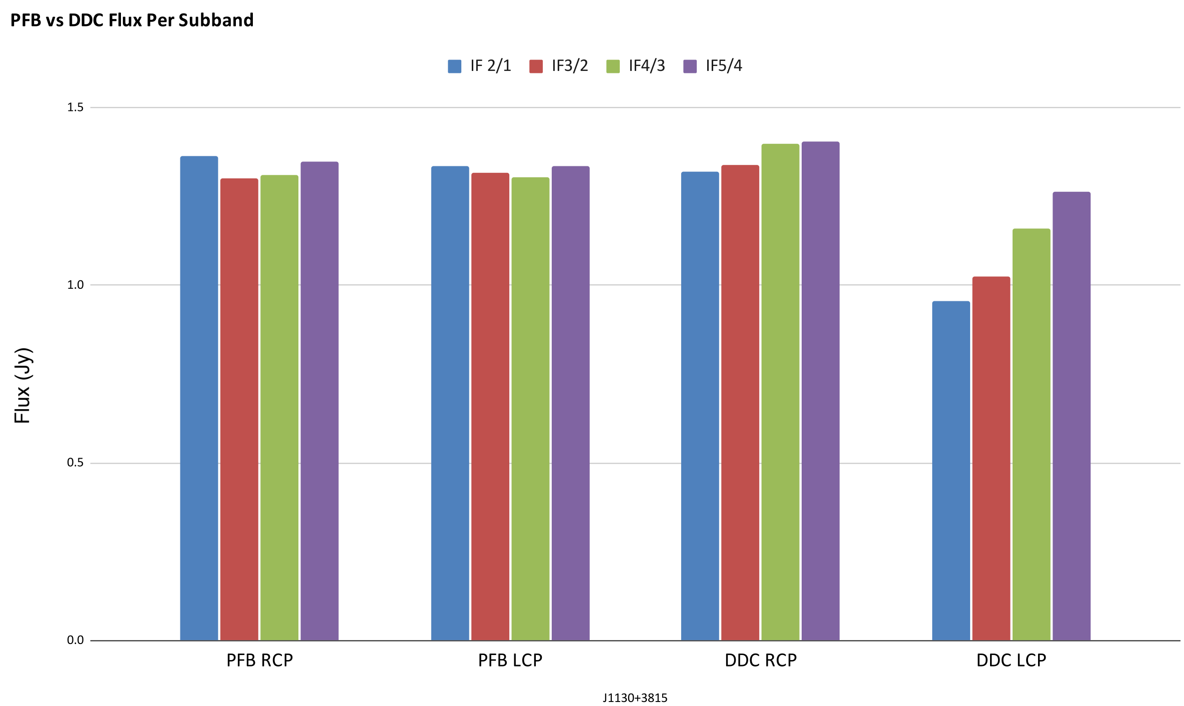

Figure 1: Loss of flux in LCP (handled by RDBE-2) when using the DDC RDBE personality. This comes from two one hour observations in PFB and DDC mode observed back to back, with 4 sub-bands set up to cover the same exact frequencies in DDC and PFB mode. Here subband 2 in PFB is the same as subband 1 in DDC (blue), subband 3 in PFB is the same as subband 2 in DDC (red), subband 4 in pfb matches subband 3 in ddc (green) and subband 5 PFB matches subband 4 DDC (purple). The flux is the flux density of a single gaussian component fitted to the core of the source. Note the fluxes agree pretty well for PFB and DDC modes in RCP but the DDC LCP flux comes out low with a pretty distinctive pattern.

VLBA consisting of 10 sites each with 2 RDBE units, it is likely that a few may be experiencing this at any given time. We were not able to determine any repeatable method of causing the effect to appear (or not), it seems totally random. It also remains unexplained why this seems to preferentially affect RDBE-2 (hence LCP) for units in the field.

3 Archival data calibration

On-sky tests confirmed that the flux discrepancy at one polarizations (LCP) is due to the DDC mode of the RDBE. The LCP data had a 10% flux density loss compared to the RCP data. However, some of these results were station-dependent and occasionally LCP was fine while RCP was off by 10%. Archival data from 2020 were examined (see Table 1) in order to confirm whether the flux discrepancy was always seen in one of the polarizations. While some loss in RCP was sometimes seen, it was much more prevanlt in LCP. The underlying cause of this is not understood.

A calibration strategy aimed at correcting archival data for this flux discrepancy issue was attempted. Data taken at different dates, and both strong and weak sources were used in an attempt to validate this strategy. When station-dependency was noticed, excluding some of the "bad" stations was also attempted.

The calibration strategy focused on transferring calibration solutions from one polarization (RCP) to the

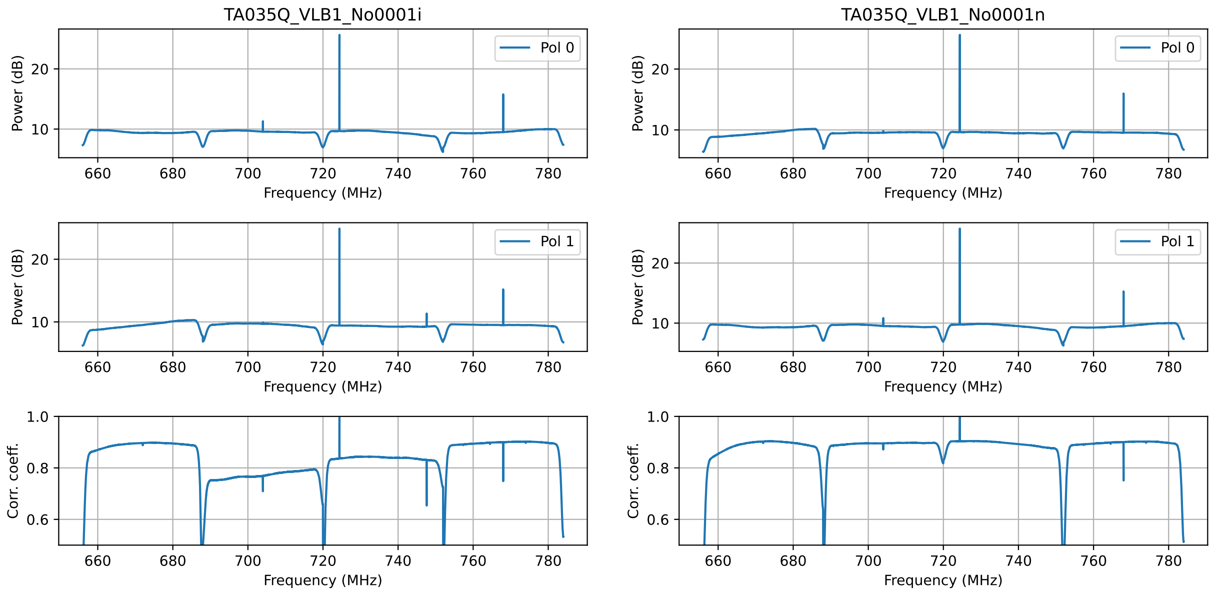

Figure 2: Two example data sets taken with the VLBA test rack lab setup, showing power (arbitrary units) and correlation coefficient C as a function of input frequency, at a frequency resolution of 3.9 kHz. Both data sets show the input tone at 724.39 MHz, the expected subband filter shapes, and spurious subband-center tones at 704 and 768 MHz. Data set TA035Q_VLB1_No0001i (left panel) additionally shows low and variable C versus subband, and a spurious image tone at 747.61 MHz in Pol 1 only. Note also that the polarization/DBE labelling was intentionally swapped between these two tests.

other (LCP) avoiding in that way the 10% flux loss of the affected polarization. The detailed procedure and tasks used in AIPS are described below. Observations used to test this calibration strategy are presented in Table 2.

MOJAVE Observations	
Block ID	Date
BL229BE	25-MAY-2020
BL229BF	13-JUN-2020
BL229BG	02-JUL-2020
BL229BH	01-AUG-2020
BL229BI	30-AUG-2020
BL229BJ	27-SEP-2020
BL229BK	01-DEC-2020
BL229BL	24-DEC-2020

Table 2: Mojave observing blocks tested for calibrating affected data.

3.1 Calibration procedure

Both calibration and imaging were done in AIPS[2], by splitting the data into two polarizations and examining them independently. Once the data were split, one image per polarization was produced. The data were

[2] http://www.aips.nrao.edu/index.shtml

self-calibrated using the RCP data only and then those self-calibration determined gains were transferred to the LCP data. A detailed description of the tasks and parameters used is shown below:

```
1. Split into RCP, "default split, stokes ’RR’"
2. Split into LCP, "default split, stokes ’LL’"

3. Make RCP image (imagr)

4. Phase self-cal RCP:
"default calib; getn RCP, get2n "the ICL file from the previous imagr",
normaliz=5, soltype ’L1R’, solmode ’P’, outname ’PselfcalRCP’"

5. Phase self-cal RCP (imagr)

6. Amp & Phase self-cal RCP:
"default calib; getn RCP, get2n "the ICL file from the previous imagr (P slefcal)",
normaliz=5, soltype ’L1R’, solmode ’A\&P’, outname ’APselfcalRCP’"

7. Amp & Phase self-cal RCP (imagr)

8. #Try to run CALIB on LCP using the image of the RCP, it will complain
due to different STOKES. You can change the header and make the RCP
image look like LCP:
a) getn X #the ICL file from the previous imagr RCP A&P image"
b) keyword = ‘crval4’
c) keyvalue = -2,0
d) putheader

9. Transfer the RCP solutions to LCP:
"default calib; getn LCP, get2n "the ICL file from the previous imagr RCP A&P image",
normaliz=0, soltype ’L1R’, solmode ’A&P’, outname ’APselfcalLCP’"

10. Amp & Phase self-cal LCP (imagr)

11. Dbcon the two calib files : APselfcal LCP & APselfcal RCP.
#(before this change the header so LCP & RCP stokes are consistent.

12. Image the output (imagr)
```

Gain solutions		
IF	Gains (beg)	Gains (end)
1	1.08	0.90
2	1.05	0.95
3	1.04	0.91
4	1.07	0.97

Table 3: Calibration gain solutions per IF transferred to LCP at the beginning (12.56 UT) and at the end (20:23) of the observing block. The gain variation over time (∼ 5hours) per IF seems to be large and hence it cannot be applied to long observing blocks.

4 Results

The flux can be recovered by solution transfer from the same source (see Figure 3), however for weak sources where self-calibration can not be applied, the method did not work. Using the gains from (for example) the phase referencing source and applying those to the target did not result in correct target flux densities. This is likely due to the variable nature of the issue as discussed in Sectionlabtests. Mojave blocks are long, spanning ~ 12 hours or more and unfortunately, when a strong source was observed at the beginning of the block, its self calibration solutions could not be applied to the weak sources taken later during the observing block (see Table 3).

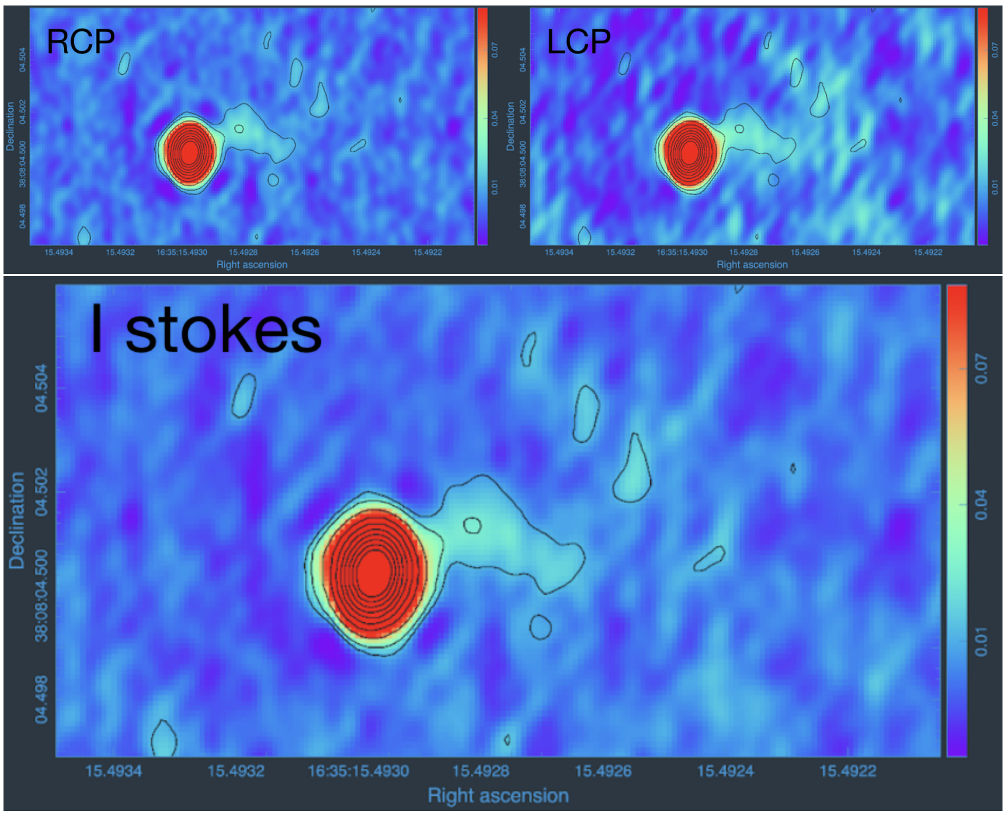

Figure 3: Final images of RCP and LCP (top) and I stokes (bottom). The flux can be recovered by solution transfer from the same source, when self-calibration is possible. Stretching and contrast is fixed to the same levels for all of them for comparison.

5 Conclusion

As no further work is being done on the RDBE personalities a full fix for this issue appears unlikely. Further testing has found no valid strategy for fixing the flux discrepancy on weak sources. It may be possible to re-scale LCP based off the RCP data when self-calibration of the target can be achieved, however care should be taken when applying this strategy. MOJAVE have worked around this issue in by simply scaling their final fluxes by 15%.

For now, if accurate (to better than 10%) flux densities are required, it is suggested that users use PFB mode. A new data buffer system (DBS) between the backend and recorder is under development which will enable dual RDBE PFB streams. This will allow for four Gbps recording using the PFB mode of the RDBEs.

We acknowledge this is not an ideal solution as the PFB mode is less configurable (i.e. allows less tuning flexibility) than DDC mode but unfortunately no better solution is currently available. In the longer term the VLBA New Digital Architecture (VNDA; Brisken et al. 2022) is being developed and will presumably not suffer from this problem.

References

MOJAVE project, https://www.cv.nrao.edu/MOJAVE/
Walker et al. 2014, VLBA Sci. Memo #37
Romney et al. 2018, VLBA Sensitivity Upgrade Memo #48
Brisken et al. 2022, VLBA, Sensitivity Upgrade Memo #52