

The ngVLA Prototype Pointing Model: Correspondence Between TPOINT and PEEK

ngVLA Antenna Memo 18

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Abstract

The present memo briefly describes the correspondence between the pointing model terms used in TPOINT and PEEK. The goal is to match the software for pointing analysis that will be used for the ngVLA prototype antenna with the current procedure followed by EVLA operations team.

1. Introduction

A telescope pointing error is well described by a model that predicts antenna offsets as a function of elevation and azimuth and depends on several terms. The offset is defined as the difference between the real position and the commanded position of a given telescope, and each term has a physical meaning, such as tilt, encoder offsets, collimation, gravitational bending, and refraction(e.g. Meeks et al. 1968, Baars 1973, Wade 1990, Greve et al. 1996, Baars 2007). The elevation and azimuth models must be obtained together since, besides the direct interdependence of the tilt terms, there are overall deformations on the structures that depend on both azimuth as in elevation changes. Although different observatories can have different strategies for obtaining the model, describing azimuth and elevation errors as a linear combination of both coordinates is a common aspect of the observatories, from radio to optical (Penalver et al. 2000, Wallace 2002, Patel et al. 2004, Mangum et al, 2006). Therefore, there is extensive literature and several tools for a good analysis (see also Dumke & MacAuliffe 2010, Kong et al. 2014 Walker 2015). Still, each telescope has its particularities, and dealing with all the terms and sign conventions can be tricky.

The ngVLA pointing recommendation is well described by ngVLA Antenna Memo 17 (Mangum 2024), and the software tool presented to obtain the pointing model is TPOINT (Wallace 2002), which is the same as the one used by ALMA (Mangum 2001). The idea is to

use TPOINT to get the model for the prototype antenna during the science verification period, which is expected to start in April 2025. TPOINT is particularly easy to handle and it does a good job with residual plots and identifying outliers and, eventually, new terms. The out-of-axis optics could add additional dependencies and extra terms could be included. It is likely that any unexpected dependence would be proportional to azimuth and/or elevation, but the understanding of the terms can be different.

Historically, VLA operation uses its own code to fit an appropriate pointing model for the antennas. It is called PEEK, written in Fortran by multiple hands. Version 1.0 is from August 1987, and while it has been on version 9.0 since September 2005, it went through several minor changes led by Ken Sowinski. The last one in 2024 to add na29 - the ngVLA prototype antenna - to its code. In the last B to A configuration change (October 2024), I computed the models using the regular and the new version of PEEK which includes na29, and both revealed the same results, as expected.

After almost 4 decades of use, VLA operations softwares are already in synchrony among them. The current system has worked since the upgrade to EVLA in 2010, although the implementation started even earlier in 2007. The TELCAL software provides the pointing solutions of a given observation in a text file that will feed as input for PEEK to get the best-fitted model, providing as output a solution that will be uploaded to the parminator and finally, the executor will get the model of each antenna on the parminator. Therefore, signs and tilt conventions are set to be understood by the entire system, and none of the parts can be understood alone. The model is done differentially, i.e., it fits the changes in each term instead of computing the absolute value.

The present memo aims to integrate the TPOINT input/output files with the VLA operation system used daily by the VLA support telescope team. The idea is to produce a document that easily translates the terms PEEK used to TPOINT description. And, of course, confirm that they both got the same model for the antennas.

2. PEEK INPUT / TELCAL OUTPUT

Figure 1 shows an example of a TELCAL output file of a pointing run, equivalent to the PEEK input file. The series of zeros on the header indicates that we will compute the differential model, i.e., we will start as if all the terms were set to zero. After that, we have the header of each scan, which contains information about wind, band, and target.

Table 1: Understanding the columns on the PNT file (Figure 1)

Ant	Pol	cosEL	sin EL	cosAz	sin AZ	ΔEL	beam	ΔAZ	beam	amp	ОТТ	old
01	R	0.9963	0.0862	0.9457	-0.325	-0.415	1.053	-0.106	1.092	0.04 3	F	F
01	L	0.9963	0.0862	0.9457	-0.325	0.113	1.049	-0.249	1.090	0.05 9	F	F

The pointing information starts after it. Each row corresponds to an antenna, with the right-hand polarization printed first. Therefore, if all 28 antennas were used, a pointing scan would provide 56 lines. The meaning of each column is shown in Table 1 for easy reading,

where beam means beamwidth and amp means amplitude. The last numerical column corresponds to the amplitude, while the two final booleans correspond to that order: if the observation was over-the-top and a former flagging label no longer used by the VLA.

```
//VER TELCAL
//RFN
              2024 119 05:32
24 119 05:32 //PAD
              01
                 W12/
24 119 05:32 //PAD
              02
                 N24/
24 119 05:32 //PAD
              03
                 E28/
24 119 05:32 //PAD
                 E04/
24 119 05:32 //PAD
                 W04/
24 119 05:32 //PAD
                 E20/
24 119 05:32 //PAD
              07
                 N20/
24 119 05:32 //PAD
              08
                 N32/
              09
24 119 05:32 //PAD
                 W20/
24 119 05:32 //PAD
              10
                 N12/
24_119_05:32 //PAD
              11
                 W08/
24 119 05:32 //PAD
              12
                 E08/
24_119_05:32 //PAD
              13
                 W32/
24 119 05:32 //PAD
                 NO4/
              14
24 119 05:32 //PAD
                 W16/
              15
24 119 05:32 //PAD
              16
                 E24/
24 119 05:32 //PAD
              17
                 N16/
24 119 05:32 //PAD
              18
                 N36/
24 119 05:32 //PAD
                 E12/
24_119_05:32 //PAD
                 W24/
24 119 05:32 //PAD
              21
                 E36/
24 119 05:32 //PAD
              22
                 N28/
24 119 05:32 //PAD
              23
                 N08/
24_119_05:32 //PAD
              24
                 W36/
24 119 05:32 //PAD
              25
                 E32/
24_119_05:32 //PAD
              27
                 F16/
24 119 05:32 //PAD
              28
                 W28/
24 119 05:32 //ANT
               01
24 119 05:32 //ANT
               02
               24 119 05:32 //ANT
            03
24 119 05:32 //ANT
               04
24 119 05:32 //ANT
               24 119 05:32 //ANT
               24 119 05:32 //ANT
            07
               24 119 05:32 //ANT
               08
24 119 05:32 //ANT
            09
               24 119 05:32 //ANT
            10
               24 119 05:32 //ANT
            11
               24_119_05:32 //ANT
            12
               24 119 05:32 //ANT
            13
               24_119_05:32 //ANT
            14
               24 119 05:32 //ANT
            15
               24 119 05:32 //ANT
               16
24 119 05:32 //ANT
               17
24 119 05:32 //ANT
               18
24 119 05:32 //ANT
            19
               24 119 05:32 //ANT
               24_119_05:32 //ANT
24 119 05:32 //ANT
               24 119 05:32 //ANT
            23
               24 119 05:32 //ANT
            24
               24_119_05:32 //ANT
            25
               24 119 05:32 //ANT
            27
               24_119_05:32 //ANT 28
               //0FS1 24 119 05:32
              1310+323 C SUBBAND: 0 REF ANT: ea12
//0FS2
                0.533786
                       12h48m39.095
                      4.83
//WX1 24 119 05:32
                3.60
                          276.55 78470.00 275.25
    24 119 05:32
                4.30
//WX2
//SUB
    1 OBSERVE FILE:
    2 DATA FILE:
   3 PROGRAM NAME: pnt bl check.60428.228998032406
//SUB
   4 SUBN: 27
//SUB 11 GDIDS1: 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 27 28
//SUB 14 BDIDS1:
01 R
    0.9963
         0.0862
               0.9457 -0.3250 -0.415 1.053 -0.106 1.092
                                           0.043 F
01 L
    0.9963
          0.0862
               0.9457
                    -0.3250 0.113
                              1.049 -0.249
                                       1.090
                                           0.059 F F
02 R
    0.9963
          0.0862
               0.9457
                    -0.3250
                          0.123
                              1.051 -0.039
                                       1.142
                                           0.056 F F
                                           0.043 F F
02 L
    0.9963
          0.0862
               0.9457
                    -0.3250
                          0.604
                              1.047 -0.210
                                       1.136
03 R
    0.9963
         0.0862
               0.9457
                    -0.3250 -0.322 1.057 -0.071
                                      1.046
                                           0.053 F F
```

Figure 1: Example of PNT file (TELCAL output and PEEK input)

PEEK works with the average between left and right polarization, with the measured value of the split between the two polarisations hard coded. Since the table is presented in sine and cosine (and not directly in elevation and azimuth), PEEK uses this boolean column to identify if it was over-the-top. The user can select a threshold for wind (typically 8 m/s at C-band and 5 m/s at X-band), bandwidth (ideal value is one, not used when the deviation is higher than 20%), and amplitude. PEEK also allows the user to fit the terms. Hardcoded in the PEEK code is the relation between the antenna's tilt and the pad's tilt and the sign angle convention used by the executor. A PEEK run produces three output files:

- PTR file: solutions of each antenna with the rms
- Changes file: which changes are significant to be updated
- gp file to make plots

Strictly speaking about VLA operations, we do not update all the parameters pointed out by PEEK without an analysis made by the team. Wind direction and weather conditions can play a role. We typically focus on recently moved antennas, where we expected a new pointing model. We are conservative in updating the model in antennas that did not move, but that may happen.

3. TPOINT input

Mangum described the TPOINT input file on ngVLA Antenna Memo 17 (Appendix A). To ensure we will be able to use TPOINT on the commissioning of the ngVLA prototype, I worked in a simple Python code to convert the TELCAL output to the TPOINT input format, with the commanded and real elevation and azimuth. A few important considerations on that file conversion:

- I obtained the commanded elevation and azimuth using the cosine and sine information of elevation and azimuth presented on the TELCAL output.
- I obtained the real elevation and azimuth after adding the measured errors to the commanded position.
- I've averaged right and left polarization errors to be appropriate with TPOINT input.
- The executor operates at a sky angle, and the TELCAL az errors must be divided by the cosine of elevation before being added to the azimuth real position.
- I converted the solutions to arcseconds (TELCAL provides solutions in arcmin and TPOINT assumes solutions in arcsecond).
- If necessary, I need to evaluate all exclusion criterions used by PEEK before running the conversion code: wind, amplitude, and beamwidth. For the tests shown here, I decided not to exclude any scans based on those quantities.

The final file corresponding to the one shown in Figure 1 is presented in Figure 2, and it is ready to be read by TPOINT. Since the prototype won't perform over-the-top observation, I've excluded them from the TPOINT modelling, although they have been used by PEEK.

4. Goals

After setting the input file for TPOINT, the major goal is to verify if TPOINT and peek point to the same solution. I followed two different strategies: (i) I reanalyzed pointing data from the

last reconfiguration with TPOINT, and I compared it with the values found by PEEK. By reconfiguration cycle, I mean (C to B move on April 24, B to A move on October 2024, A to D move on February 25, D to C on May 25 move and again C to B move on August 25). That is, in fact, a verification of the differential model strategy. (ii) We have set a model of one particular antenna to zero (ea04) and have fitted both PEEK and TPOINT to check the solutions.

```
VLA Antenna Test Facility: Test to ngVLA prototype
: ALTAZ
: ALLSKY
34 4 24.636 !
! az, el, azEnc, elEnc, offx, offy, centx, centy, s2n
    109.10017
                  85.08219
                              108.96879
                                            85.05748 !
                                                            1310+323
                                                                        0
    334.53102
                  73.59902
                              334.67479
                                            73.59867 !
                                                            1310+323
                                                                        2
                                            42.60947 !
    356.12828
                  42.62547
                              356.19862
                                                            1310+323
    352.25273
                  12.56528
                              352.30696
                                            12.55215 !
                                                            1310+323
                                                                        6
    329.10096
                  22.79165
                              329.15884
                                            22.79522 !
                                                            1310+323
                                                                        8
    281.90425
                  14.21128
                              281.95601
                                            14.23433 !
                                                            1310+323
                                                                        10
                  32.16130
                              302.39648
                                            32.17870 !
    302.33763
                                                            1310+323
                                                                        12
    293.94865
                  69.78639
                              294.05849
                                            69.80805 !
                                                                        14
                                                            1310+323
    257.45363
                  83.12828
                              257.53451
                                            83.15652 !
                                                            1310+323
                                                                        16
    224.34078
                  46.06192
                              224.38557
                                            46.08560 !
                                                            1310+323
                                                                        18
                                            18.52286 !
    228.17165
                  18.49910
                              228.22166
                                                            1310+323
                                                                        20
    204.96189
                  11.90994
                              205.01004
                                            11.93060 !
                                                            1310+323
                                                                        22
    168.25411
                  16.92117
                              168.29852
                                            16.92287 !
                                                            1310+323
                                                                        24
                  40.44796
                              181.39822
                                                                        26
    181.36371
                                            40.45759 !
                                                            1310+323
                                                                        28
                  84.36658
                              178.60178
                                            84.37848 !
                                                            1310+323
    178.83851
                  83.62279
                                            83.64103 !
                                                                        30
    208.89447
                              208.78444
                                                            1310+323
    120.46372
                  44.41740
                              120.50100
                                            44.39088 !
                                                            1310+323
                                                                        32
    116.20115
                  17.26168
                              116.24776
                                            17.23503 !
                                                            1310+323
                                                                        34
     80.62861
                  25.25110
                               80.67938
                                            25.21784 !
                                                            1310+323
                                                                        36
     56.67770
                  16.71696
                               56.73065
                                            16.68503 !
                                                            1310+323
                                                                        38
                               68.24939
                                            50.07530 !
                                                                        40
     68.19323
                  50.10857
                                                            1310+323
    126.49032
                  47.39187
                              126.53062
                                            47.36838 !
                                                            1310+323
                                                                        42
    122.15672
                   9.30383
                              122.20521
                                             9.28456 !
                                                                        44
                                                            1310+323
     83.92078
                  31.11165
                               83.97531
                                            31.07507 !
                                                            1310+323
                                                                        46
                                            17.07964
     67.02043
                  17.11487
                               67.07237
                                                            1310+323
                                                                        48
                  55.45437
     68.92782
                               68.99393
                                            55.41860 !
                                                            1310+323
                                                                        50
     32.01441
                  78.17406
                               32.15718
                                            78.14939
                                                            1310+323
                                                                        52
    355.03666
                  79.19600
                              355.20475
                                            79.18375
                                                            1219+484
                                                                        54
    358.52895
                  41.97801
                              358.59647
                                            41.96225 !
                                                            1219+484
                                                                        56
    357.96192
                  18.15200
                              358.01506
                                            18.14028 !
                                                            1219+484
                                                                        58
    320.12067
                  15.73676
                              320.17345
                                            15.74101 !
                                                            1219+484
                                                                        60
                                            21.12505 !
    283.00094
                  21.10510
                              283.05354
                                                            1219+484
                                                                        62
    297.12167
                  44.54788
                              297.18540
                                            44.56263 !
                                                            1219+484
                                                                        64
                  77.89879
                              335.03891
    334.87514
                                            77.89753 !
                                                            1219+484
                                                                        66
    207.25841
                  71.30317
                              207.24764
                                            71.32103 !
                                                            1219+484
                                                                        68
    234.12485
                  38.15660
                              234.17210
                                            38.17860 !
                                                            1219+484
                                                                        70
    251.07069
                  22.67016
                              251.12207
                                            22.69148 !
                                                            1219+484
                                                                        72
    207.54805
                  15.33840
                              207.59595
                                            15.35625 !
                                                            1219+484
                                                                        74
                  17.87409
    172.18176
                              172.22713
                                            17.88083 !
                                                            1219+484
                                                                        76
      5.68983
                  76.73546
                                5.84575
                                            76.72285 !
                                                            1219+484
                                                                        78
                  49.91515
                                                                        80
    355.33815
                              355.41498
                                            49.90324 !
                                                            1219+484
    351.09847
                  14.61416
                              351.15179
                                            14.60251 !
                                                            1219+484
                                                                        82
    329.12487
                  24.53888
                              329.18120
                                            24.53680 !
                                                            1219+484
                                                                        84
```

Figure 2: Converted file presented in figure 1 to be read by TPOINT for ea04.

5. Nomenclature

Below is a general notation for the pointing equation, where equation (1) corresponds to the azimuth error and equation (2) corresponds to the elevation error.

$$\Delta Az \cos(El) = C_1 + C_2 \cos(El) + C_3 \sin(El) + C_4 \cos(Az) \sin(El) + C_5 \sin(Az) \sin(El)$$

$$+ C_6 \cos(Az) \cos(El) + C_7 \sin(Az) \cos(El) + C_8 \cos(2Az) \cos(El) + C_9 \sin(2Az) \cos(El)$$

$$+ C_{10} \cos(3Az) \cos(El) + C_{11} \sin(3Az) \cos(El)$$
(1)

$$\Delta El = D_1 + D_2 \cos(El) + D_3 \sin(El) + D_4 \cos(Az) + D_5 \sin(Az)$$

$$+ D_6 \cos(2Az) + D_7 \sin(2Az) + D_8 \cos(3Az) + D_9 \sin(3Az)$$
(2)

Although the physical meaning is given by the sine and cosine dependence of each term, there are a variety of names and labels that depend on each observatory. At VLA high order terms, i.e., 2AZ and 3AZ are not used, and the tilt terms C4/D5 and C5/D4 are connected. A more simple and useful version of the equation is presented below, which also considers the tilt terms interdependence (Baars 2007):

$$\Delta Az \cos(El) = P_1 + P_2 \cos(El) + P_3 \sin(El) + P_4 \sin(El) \cos(Az) + P_5 \sin(El) \sin(Az)$$

$$\Delta El = P_6 + P_7 \cos(El) - P_4 \sin(Az) + P_5 \cos(Az) + P_8 (\cos(El)/\sin(El))$$
(4)

There is also a diversity of sign notation; while PEEK uses the classical notation presented above (named Stumpff notation, Stumpff 1972), TPOINT uses a different one, flipping the sign of the azimuth terms (identified by Baars as Wallace notation - see also ngVLA Antenna Memo 17 and Wallace 2002). In Table 1, I present a dictionary of the various terms and how the parminator identifies them.

The refraction term (P8) is typically tiny, It can be found independently and it has no affect on the other terms of the pointing model. Therefore, we do not change it during VLA regular operation, and I won't consider it in the TPOINT and PEEK correspondence analysis (for completeness, the refraction term is identified as REFR in PEEK solutions). The terms A3, A4, and E4 in PEEK represent the encoder center errors in Azimuth (EW and NS direction - C6 and C7 in equation 1) and Elevation (horizontal plane - D3 in equation 2). Typically, for the VLA antennas, they are small and stable terms, and we can find a suitable model that only fits the P terms of equations 3 and 4. At EVLA, those items were updated by Ken mostly in 2015 - but for a few antennas, it is from the pre-EVLA era.

Finally, it is essential to have measurements well spread around the space of parameters (azimuth and elevation) to obtain a reliable pointing model.

Table 1: Sign and terms conversion between Parminator, Peek and TPOINT

Term	Parminator	Conversio n Parminator to Peek	Peek Parameter	Conversion Peek to TPOINT	TPOINT Parameter
P1	AZCOL	1	A6	-1	CA
P2	AZENC	1	A7	-1	IA
P3	PERPENDICULARITY	1	A5	-1	NPAE
P4	NSTILT	1	A2/E2	-1	AN
P5	EWTILT	-1	A1/E1	-1	AW
P6	ELCOL	1	E5	1	ΙE
P7	ELCENTERINGCOS	1	E3	1	ECEC

6. Results: Correspondence between TPOINT and PEEK

I will present the results of both strategies (6.1 and 6.2). But first, I must explain how the VLA operation team handles the tilt terms. The tilt on VLA is a combination of two terms: the antenna tilt and the pad tilt. We can not separate between them when we model the pointing errors. Therefore, we use the master pad to separate those terms. When we measure the pointing errors in an antenna in the master pad, where we know the pad tilt, we assume that the errors are due to the antenna tilt. When an antenna is not on the master pad, we attribute the errors to the pad tilt. That won't be an obstacle to our tests, but we must consider how the executor combines antenna and pad tilt on section 6,2, where we aim to obtain the absolute pointing model. Finally, for convenience, I opt to work in arcsec on section 6.1 and in arcmin on section 6.2 (for a direct check with the parminator).

6.1 Differential Pointing model on the current base

TPOINT was used on former VLA pointing data to validate it to the ngVLA prototype. We did not get new data, we have used data from the previous VLA reconfiguration (see Section4). Since we are working with a differential pointing model during EVLA operations, we do not fit ECEC and CA because we do not expect those quantities to change. Therefore, for this first analysis, we have modeled only five terms of table 1: NSTILT (North-South Tilt), EWTILT (East-West Tilt), AZENCZERO (Azimuth zero of the encoders), PERPENDICULARITY (a non-perpendicularity of the azimuth axis) and ELCollimation (Collimation in the elevation direction).

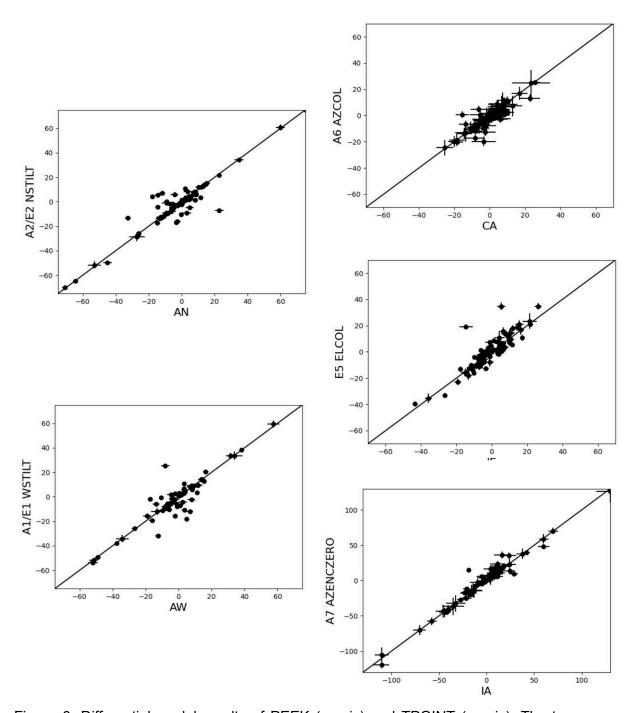


Figure 3: Differential model results of PEEK (y axis) and TPOINT (x axis). The terms are presented in arcsec.

In Figure 3, I show the correspondence between those five terms of the pointing model, computed using PEEK and TPOINT. The codes use different fitting algorithms, so there are minor differences in the results that may become larger on noise or sparse datasets. Typically, we fit 36 points around the celestial sphere, and the results using both codes trend to an agreement that we have a more sampled space of parameters. Anyway, despite an outlier, the results generally agree even in short runs with 36 scans - which also validates the conversion file script I made.

A quick comment needs to be made on the errors. Since they use different algorithms, they are slightly different. The peek uses linear regression to estimate the errors, while TPOINT penalizes the small sample that we use to get the model, which explains the higher errors on the x-axis.

Additionally, to increase the sample size, I have included long pointing runs that extend beyond the top, which affected PEEK solutions. Even then, the differences are majority in less than 10 arcsecs, which is the VLA accuracy for the global pointing model. In total, I have used 86 datasets from diverse antennas: 10 at C band and 76 at X band. Figura 4. I show a histogram of the differences between TPOINT and PEEK, considering all five parameters (total sample of 430), 392 are within 10 arcsec of difference. In Figure 4, I show the total histogram in bins of 1 arcsec.

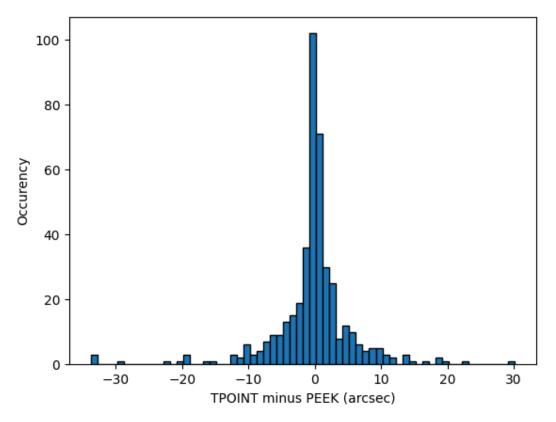


Figure 4: Histogram showing the differences between TPOINT and PEEK for the five pointing model parameters in our sample

6.2 Absolute pointing model of ea04

For the second strategy, I have used a special version of the pointing script used by the VLA operation to get pointing errors around the sky. Ken Sowinski made changes to set all terms of the model to zero before starting any scan. That choice was preferred over changing all the parminator terms to zero, so we would prevent our tests from interfering with any user observation by mistake. The disadvantage of such a strategy, we realize after running the test, is that during the interferometric pointing scan, the executor gets the collimation terms directly from the parminator, regardless of whether we have set them to zero prior to the

scan. In other words, they were not set to zero as our initial intent. Below I summarize the main characteristics of the test:

- The collimation term in elevation and the perpendicularity plus collimation in azimuth
 were not set to zero. So, if we aim to fit an absolute pointing model, those terms need
 to be close to zero. That is more critical in the Azimuth error because there is a
 degeneracy between the perpendicularity and the AZ collimation term that requires a
 large dataset to be resolved.
- The tilt term set to zero encompasses the pad and the antenna tilt.
- All the other terms are set to zero.
- In total I have combined 3 observation days, totalizing 82 observations, which 20 of them were over-the-top.

I chose to use antenna ea04 because it had minor values on the model, and I could ensure we would not miss the target by setting the pointing model terms to zero. The ea04 also has the advantage of being close to the center of the array during our observations. The observation was performed on April 20th, May 20th, and June 3rd, 2024, and mostly during nighttime at C-band. We tried to get data with wind no higher than 8 m/s, but a few observations were obtained with higher wind. Nevertheless, we did not exclude any observation in the analysis. The script used is called pnt_bl_check.evla. On June 3rd, operations ran the script for two hours, soon after the usual C-band pointing script, which we could use as a reference if needed.

Table 2: Model solution using PEEK and TPOINT and the expected values. For the collimation terms where we expected zero, I show the value of Parmiantor in parenthesis. All values are in arc minutes.

values are in all minutes.							
TERM	NAME	EXPECTED	PEEK	TPOINT			
CA	AZCOL	0.30	0.36 ±0.18	0.32±0.45			
IA	AZENC	-3.28 -3.27 ±0.11		-3.23 ±0.36			
NPAE	PERPENDICULARITY	-0.51	-0.35 ±0.20	-0.30±0.38			
AN	NSTILT	0.63	0.56 ±0.03	0.58 ±0.04			
AW	EWTILT	1.50	1.56 ±0.03	1.54 ±0.04			
IE	ELCOL	0.00 (3.59)	0.09 ±0.04	0.11 ±0.08			
ECEC	ELCENTERCOL	0.19	0.23 ±0.06	0.19 ±0.11			
CA plus NPAE	AZCOL+PERP	0.00 (0.21)	0.01 ±0.38	0.02 ±0.83			

In Table 2, I present the model fitted with Peek and TPOINT and the expected values (i.e., the values given in the Parminator, which was the model we had been using for ea04). To recover the expected pad tilt terms, I needed to read the antenna term and use equations (5) and (6) to get expected terms, since we had set everything to zero and we are fitting the total term. I also need to know the absolute pad tilt. That won't be necessary for the ngVLA

prototype since the executor will not have a priori term to the test pad as we have now, and the tilt term we found can be directly fed in the parminator.

$$EWTILT_{total} = EWTILT_{pad} + \cos(Az_{pad})EWTILT_{ant} - \sin(Az_{pad})NSTILT_{ant}$$
(5)

$$NSTILT_{total} = NSTILT_{pad} + \sin(Az_{pad})EWTILT_{ant} + \cos(Az_{pad})NSTILT_{ant}$$
(6)

Where the total east-west tilt ($EWTILT_{total}$) and the north-sourth tilt ($NSTILT_{total}$) are written as a function the tilt terms of the antenna ($EWTILT_{ant}$ and $NSTILT_{ant}$) and the tilt terms of the pad ($EWTILT_{PAD}$) and $NSTILT_{PAD}$). The Az_{pad} corresponds to the azimuth of the pad, which is also present in the parminator. Since the total tilt was set to zero in our tests, we need to combine those terms on the parminator to get the expected value presented in Table 2.

Finally, because of the degeneracy of small datasets of the azimuth terms perpendicularity and collimation - meaning that they mascarade each other. As I mentioned above, the reader will notice that they both tend to zero together because they were not set to zero in our observations. I added an extra line in Table 2 to show it. It is curious that both PEEK and TPOINT were close to separate the absolute value of those terms, even with higher errors.

ACKNOWLEDGEMENT

I appreciate the discussion I had with Jeff Mangum and Ken Sowinski during the attempt to translate the PEEK solutions to the TPOINT values. I also appreciate the feedback Jeff provided on the memo text. I also thank Daniel Faes for working on a code to extract the value of the parminator on a given day; that made my work on the present memo easier.

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