EVLA Memo 241

Validating AstroHACK: OTF Holography

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Abstract

AstroHACK is a new Python package used to analyze holographic measurements from the VLA, ALMA, and the ngVLA prototype. It is currently being developed by a subgroup within the NRAO DMS Data Processing Division aimed at providing tools for telescope support. In this work, we present the validation of AstroHACK using holographic measurements of VLA antennas obtained with the on-the-fly mode. Historically, AIPS has been successfully used to analyze interferometric data at the VLA and to derive panel corrections that improve antenna performance at high frequencies. We demonstrate that AstroHACK produces images and panel corrections consistent with those obtained using AIPS for on-the-fly holography. This memo describes the validation tests performed and their results.

1 Introduction

The development of the ngVLA prototype has motivated a new series of tests related to the holography mode of the VLA. A major change has been the implementation of the on-the-fly mode (hereafter OTF). The tests relating to the validation of this new mode are presented in the EVLA Science Memo 237 (Beaklini 2024).

Parallel to the effort to validate the OTF holography mode, the DMS[1] Data Processing Division[2] has started developing a new software tool to analyze holography data, both Point & shoot and OTF, with the goal of supporting the commissioning of the ngVLA prototype antenna. Therefore, the present memo focuses on the OTF mode, while development for the Point & shoot mode is still ongoing. The goal is for this new tool to support the current VLA antennas as well as the ngVLA prototype, and potentially other observatories in the future, such as ALMA. The new package was named AstroHACK, an acronym for Astronomy Holography Antenna Commissioning Kit. Although it is developed by members of the DMS Data Processing division, AstroHACK is not distributed with CASA and therefore requires a separate installation.

As already explained in Memo 237, the validation of two new capabilities at the same time is not a good plan. Therefore, although AstroHACK was also used during the OTF holography validation, Memo 237 reported only the results obtained with AIPS. Meanwhile, AstroHACK has remained under active development during this process. In the present Memo, we analyze the same OTF dataset used to validate this observing mode, now focusing on the validation of AstroHACK. We do not intend to provide an in-depth discussion of the code or extensive documentation on its use here. The goal is to show that it works and that it is reliable.

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[1] Data Management and Software division of NRAO.

[2] Previously known as the CASA team.

Future publications will ensure that those questions are appropriately addressed, and there are also extensive details on its tutorial.

It is also worth noting that although the software package was originally intended to analyze holography data, it has enlarged its scope to address other issues of telescope support, such as updating the VLA baselines after an antenna moves to a new pad. Each capability will have its own Memo, so no features other than holography will be discussed here.

The present memo provides a concise summary of the work carried out over the past three years. In this memo, we present data demonstrating that AstroHACK can be reliably used to process OTF holography observations for the VLA.

1.1 Brief description of AstroHACK

AstroHACK is a pure Python package developed by a subgroup within the Data Processing Division as part of the RADPS initiative. The main goal of AstroHACK is to support telescope operations that still rely on AIPS, such as holography and antenna position corrections. The project github page can be found at `https://github.com/nrao/astrohack` and its ever crescent documentation, including python notebook tutorials, can be found at `https://astrohack.readthedocs.io/`.

The holography tasks in AstroHACK port the functionality of AIPS holography tasks (UVHOL, HOLOG and PANEL) to a modern python framework, while expanding holographic capabilities with the addition of Zernike polynomial fitting of apertures. The new python framework enables AstroHACK to take advantage of modern parallelization and code acceleration technologies, such as numpy, Dask and Numba. Making the reduction of holography data much faster, and streamlined for the user.

AstroHACK does not intend to perform calibration. The calibration of the data presented here was done in CASA. AstroHACK takes an MS V2 file as input, and it reads by default the CORRECT_DATA column, although it can also read the uncalibrated DATA column if needed.

2 Methodology

We follow the same strategy adopted in EVLA Memo 237, and several sections refer back to it. We suggest that the reader review the definitions introduced in that memo, in particular the definition of an error of 15 mils in the screw adjustments.

For a simple and qualitative analysis, we will present the surface deviation maps for antenna EA03 in Section 3.1. A simple visual inspection shows that the surface deviation maps are equivalent. Although several maps were obtained, we focus on the data used in the OTF validation. During this period, several holographic measurements were also taken at different frequency bands.

As a more quantitative approach, we present the surface RMS values of the dishes obtained with AstroHACK and compare them with the results from AIPS. Finally, EVLA Memo 237 presents the results of a blind test in which three panels were intentionally displaced by the VLA Antenna team to verify whether the holography analysis could recover those offsets. Although the displacement introduced by the team was not significantly above the noise level, AIPS was able to recover values close to the applied offsets. In this memo we show that AstroHACK can reproduce these results.

3 Results

We divide the results into two subsections. First, we present the surface maps of all antennas used in the OTF validation at Ka band. Then, we present the correlation between the surface RMS of several antennas and the accuracy of the blind test used to validate the OTF technique.

3.1 Surface Deviation Maps

In figures 1 and 2 we show two examples of surface deviation map comparisons between AstroHACK and AIPS, one for the OTF mode, the other for the Point & shoot mode. In these figures it can be seen that the residual images are mostly featureless, except for small features that appear near the edges of the surface deviation map. This region of the maps is more prone to such issues as the aperture amplitudes here are smaller, increasing the phase error and hence decreasing the surface deviation map accuracy. In most cases these features appear to be around + or - 0.5λ, indicating that a phase wrap occurred.

The agreement between the maps is evident. The remainder of the surface deviation maps can be seen in the appendix (sections A and B). We show here only surface deviation maps obtained during the OTF validation tests, when half of the array was used to compare the Point & shoot and OTF observing modes. Visual inspection indicates full agreement between AstroHACK and AIPS.

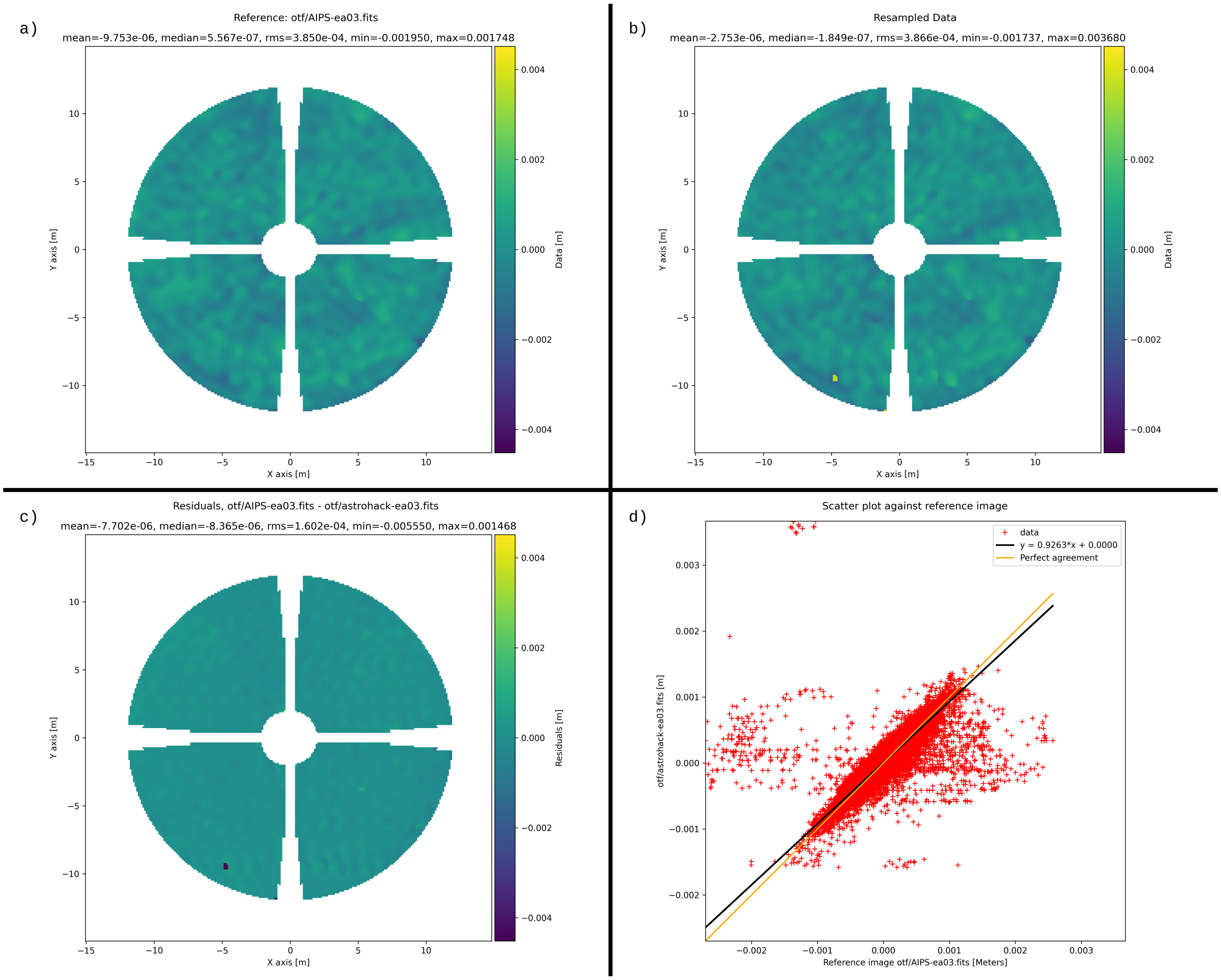

Figure 1: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA03: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

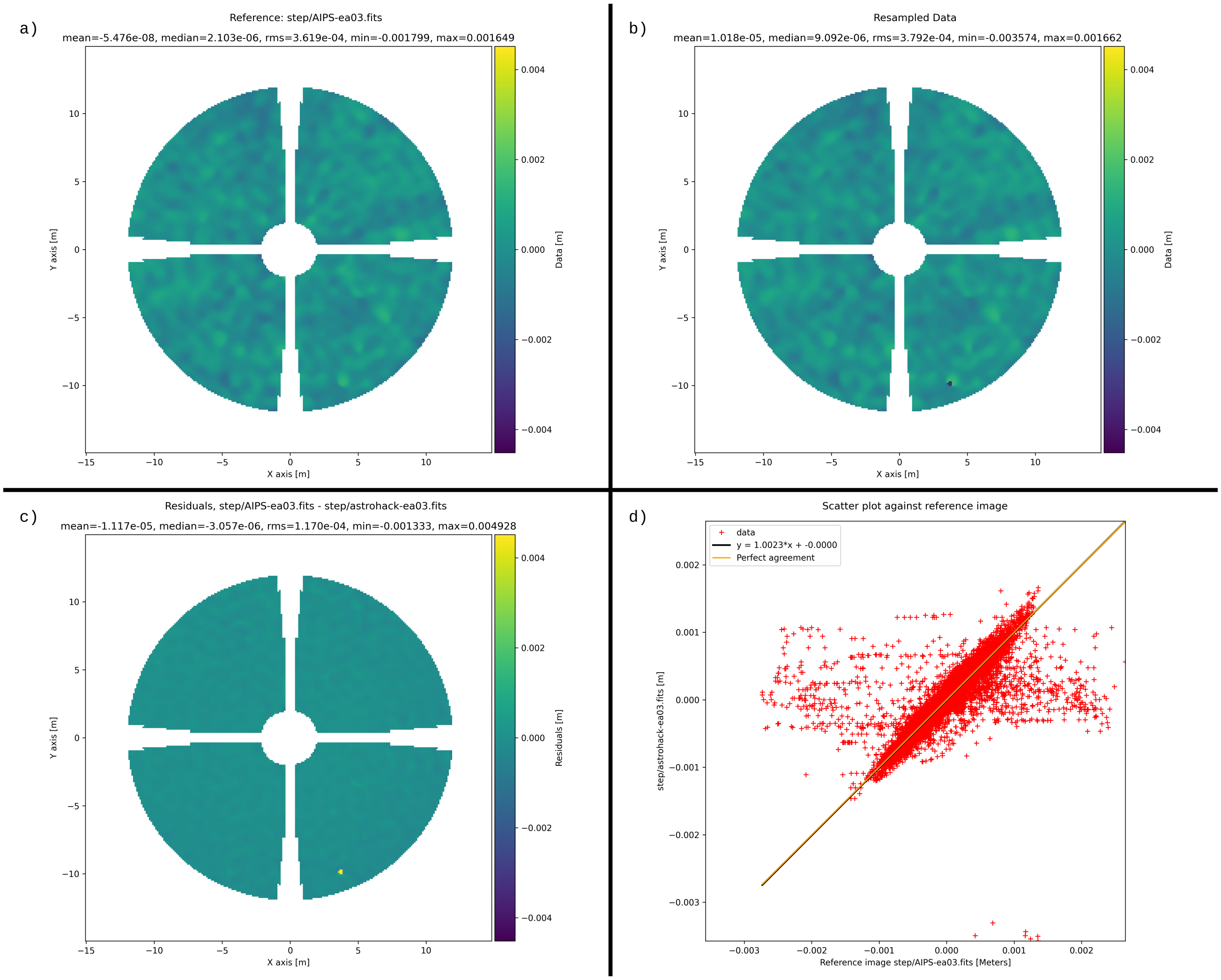

Figure 2: Point & shoot holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA03: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

3.2 Surface RMS and Screw accuracy

In Figure 3, we present a more quantitative comparison between AIPS and AstroHACK. Using the same Ka-band dataset, we compare the surface RMS obtained for the scanned antennas using both software packages. The uncertainty in the surface RMS is about 6 μm (see Table 1 of EVLA Memo 237). Although we focus on the OTF mode, we also include the solutions obtained using the point-&-shoot mode (data from December 2022), which show similarly good agreement. The surface RMS uncertainty for this mode is about 20 μm.

Since each software package uses its own mask to get the surface rms and we would like to do a apples to apples comparison, we have exported all the images to FITS files and run an AstroHACK tool for comparing FITS images that added a standard mask representing the VLA blockage (i.e. the subreflector and its support structure). The surface RMS was obtained after applying such a mask, so it is independent of any clip value in amplitude. AstroHACK uses this type of blockage mask for all VLA holography reductions.

The final results, shown on the left, indicate good agreement between the surface deviation RMS values obtained using AIPS and AstroHACK. A similarly good agreement is found when comparing the screw adjustments for all antennas. The results are presented in units of λ to avoid confusion due to phase wrapping. For these observations, $\lambda \approx 9$ mm, and the typical error of 15 mils corresponds to $\sim 0.003, \lambda$. Overall, the results show good agreement between the two software packages.

Finally, below we show the results of the blind test performed on April 21, 2025, when the VLA Antenna mechanics team displaced three panels by a small amount. The applied displacement was close to the noise level, but both AIPS and AstroHACK recovered values close to the expected ones. A positive sign means lowering the panel away from the subreflector, while a negative sign means raising the panel toward the subreflector. The screw order is: inner-edge-left, inner-edge-right, outer-edge-left, and outer-edge-right (all values presented below are in mils):

- For panel 3-16:
  - Truth: +15 +15 -15 -15
  - AIPS recovered: +12 +12 -12 -19.
  - AstroHACK recovered: +10 +9 -8 -20.
- For panel 4-6:
  - Truth: +20 +20 +20 +20.
  - AIPS recovered: +23 +15 +18 +08.
  - AstroHACK recovered: +19 +23 +16 +20.
- For panel 5-36:
  - Truth: -20 -20 -20 -20.
  - AIPS recovered: -11 -14 -06 -19.
  - AstroHACK recovered: -2 -17 +9 -9.

From a direct analysis of the numbers, we can say that AIPS recovered panels 3-16 and 5-36 better, while AstroHACK recovered closer solutions for panel 4-6. However, both solutions are very close and reinforce the conclusion that the applied displacement was near the noise level. Even under these conditions, both software packages recovered values very close to the true offsets.

We obtained these results using a Gaussian interpolation gridding mode, a padding factor of 10, an amplitude clipping level of 1.0, and a flexible panel model with an excluded panel margin of 5%[3]. All these parameters, except the clipping level, are set to their default values in AstroHACK. By default, the clipping level is set according to the RMS noise in the amplitude map.

4 Discussion

As Rick Perley pointed out in EVLA Memo 212, the surface deviation RMS of the VLA antennas does not change rapidly; it remains stable over several years. In this memo, we compare screw adjustments whose values are close to the noise level. Although the dataset is the same, different minimization procedures can lead to small fluctuations around the best-fit solution. Therefore, some level of spread is expected when comparing screw solutions between AstroHACK and AIPS (see the middle and left panels of Figure 3). However, the spread in the differences is comparable to the error level, which makes the solutions physically equivalent.

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[3] Please check the AstroHACK API documentation for a full description of the input parameters.

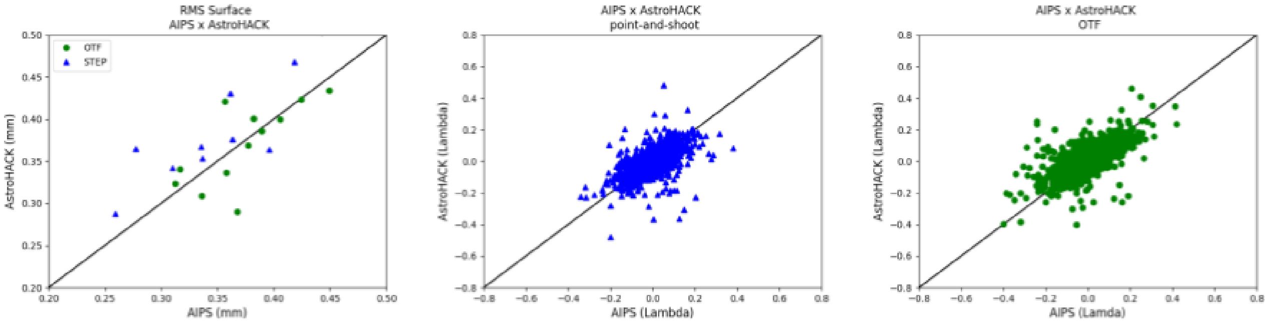

Figure 3: Left: Surface RMS obtained for all antennas listed in Table 1 using AIPS and AstroHACK. The surface RMS is shown in mm, and the uncertainty for these datasets is 6 μm for the OTF mode and 20 μm for the Point & shoot mode. Middle and right: Screw adjustments derived by each software package for the same antennas. A typical error of ±15 mils corresponds to $\sim 0.03, \lambda$ at the Ka band ($\lambda \approx 9$ mm).

During regular operations, we do not adjust screws unless they are significantly out of position, which can be identified using both AIPS and AstroHACK. In 2023, we agreed with the Antenna team to adjust screws when the AIPS solution indicated values around 30 mils. We tested such a level of panel adjustment on EA06 and it did not produce a significant improvement in antenna performance. Loose panels are more relevant to adjust and can significantly improve the panel surface RMS, such as the case reported for EA16 (see EVLA Memo 237). These scenarios are evident using both software packages.

The ngVLA prototype project plans to use AstroHACK to assess the surface quality of the antenna. AstroHACK already includes ray-tracing capabilities for the ngVLA prototype dish. These capabilities cannot be fully validated until the antenna becomes available for holography tests. However, the experience gained so far and the growing collaboration between the operations team and the AstroHACK development team should help overcome any potential issues.

5 Conclusion

AstroHACK is ready to be used with the ngVLA prototype antenna and to be incorporated into regular VLA operations. We recognize that minor changes may be required to address potential challenges during the commissioning of the prototype. However, the current version is ready for use with the VLA antennas.

We recognize that there is no urgency to change the software currently used in New Mexico operations, since AIPS continues to perform well for panel adjustments. For upcoming holographies, the plan is to obtain results with both AIPS and AstroHACK and continue following the strategy of comparing the two software packages. We will also continue comparing the calibration results obtained with AIPS and CASA.

AstroHACK may also be used in several other tests we are currently conducting with the new OTF holographic mode. It is a powerful and user-friendly tool that we hope will encourage others to obtain and analyze holographic measurements. AstroHACK also allows quick fitting of beam cuts, a feature that still needs to be validated.

As a final comment, we have not explicitly relied on the Point & shoot mode in the current memo because we are still not satisfied with the AstroHACK solutions in some cases. Namely, older Point & shoot holographies where there is significant non-uniformity in the pointing tables. However, this is a path we are still pursuing. As seen in Figures 3 and 2, the surface deviation maps, surface RMS values and the screw corrections already look very similar. We decided to proceed with the OTF validation independently in order to document AstroHACK validation before the ngVLA prototype interferometric tests start[4].

Acknowledgements

We would like to acknowledge Jeff Mangum for the discussion and ideas to validate AstroHACK.

References

[1] Beaklini, P.P.B., 2024, EVLA Memo 237
[2] Perley, R., 2021, EVLA Memo 212

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[4] scheduled for April 2026.

A Point & shoot surface deviation map comparison

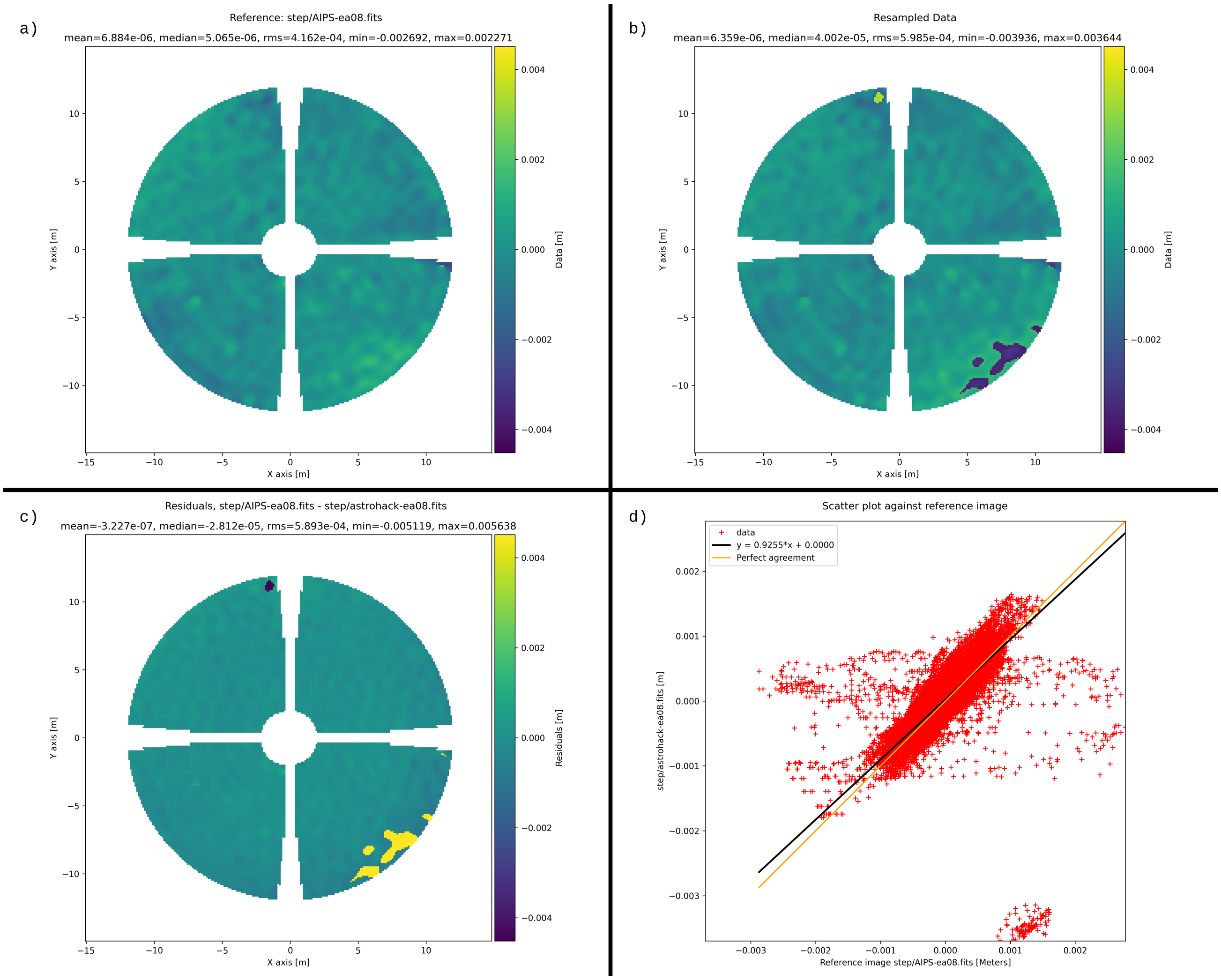


Figure 4: Point & shoot holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA08: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

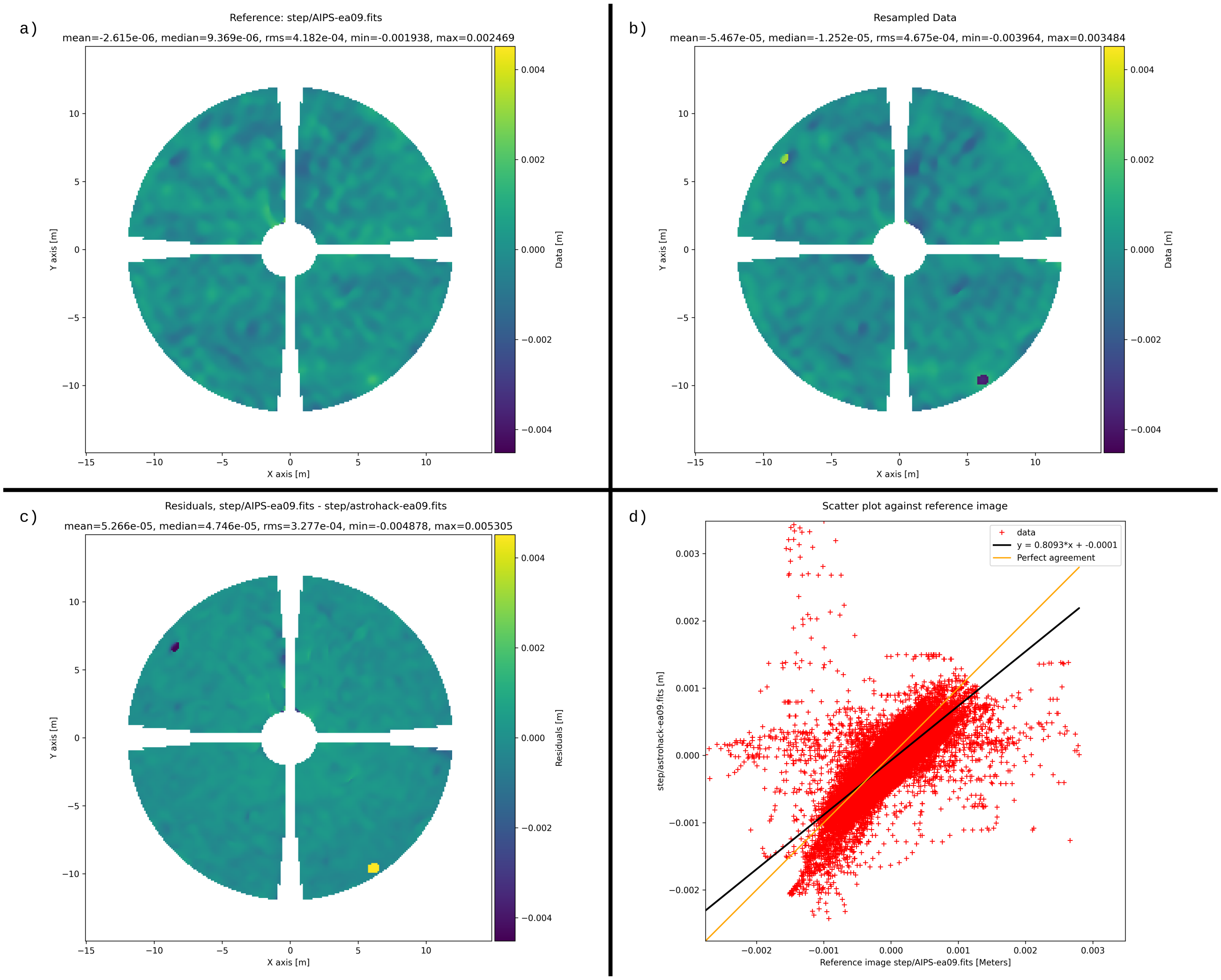


Figure 5: Point & shoot holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA09: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

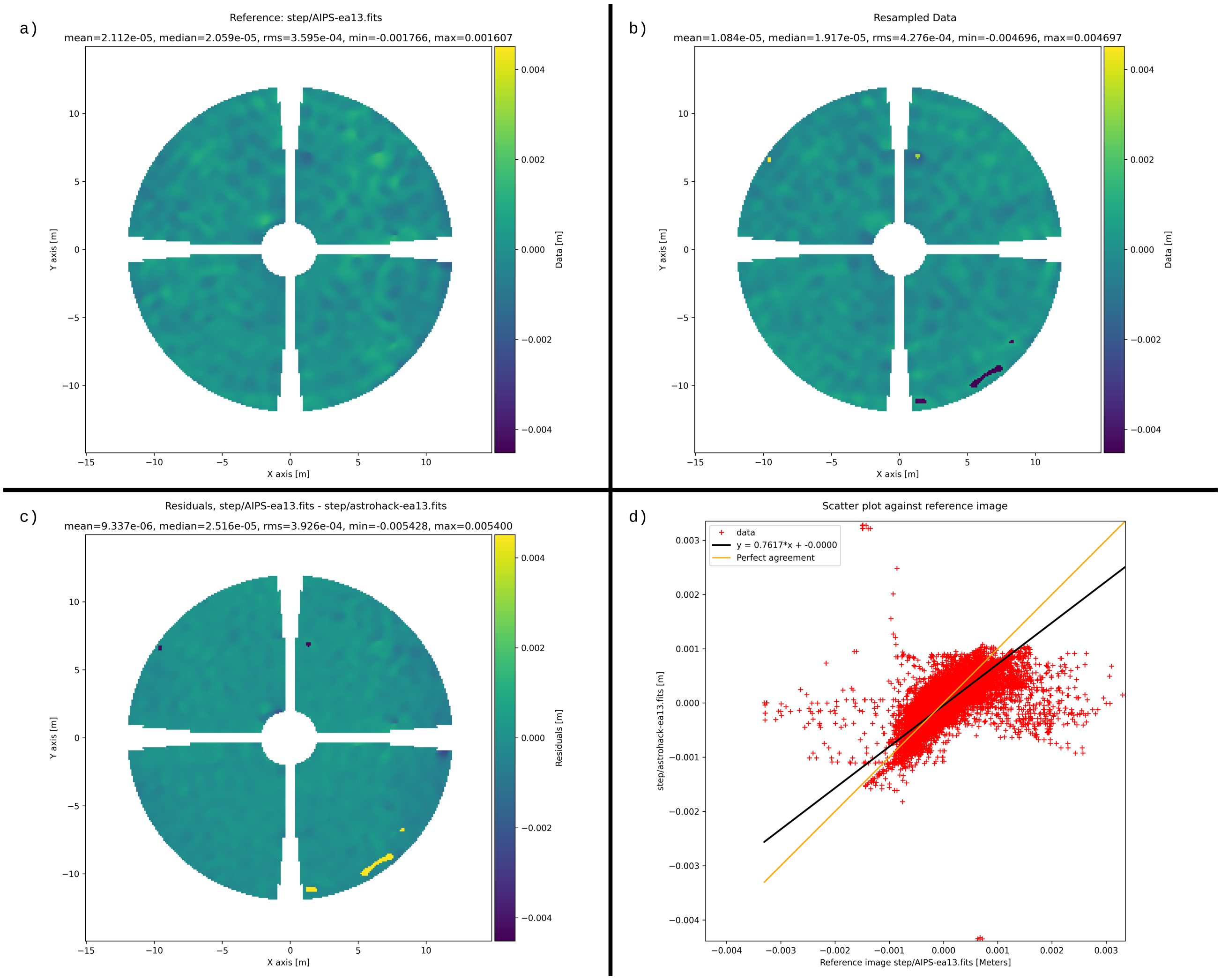


Figure 6: Point & shoot holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA13: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

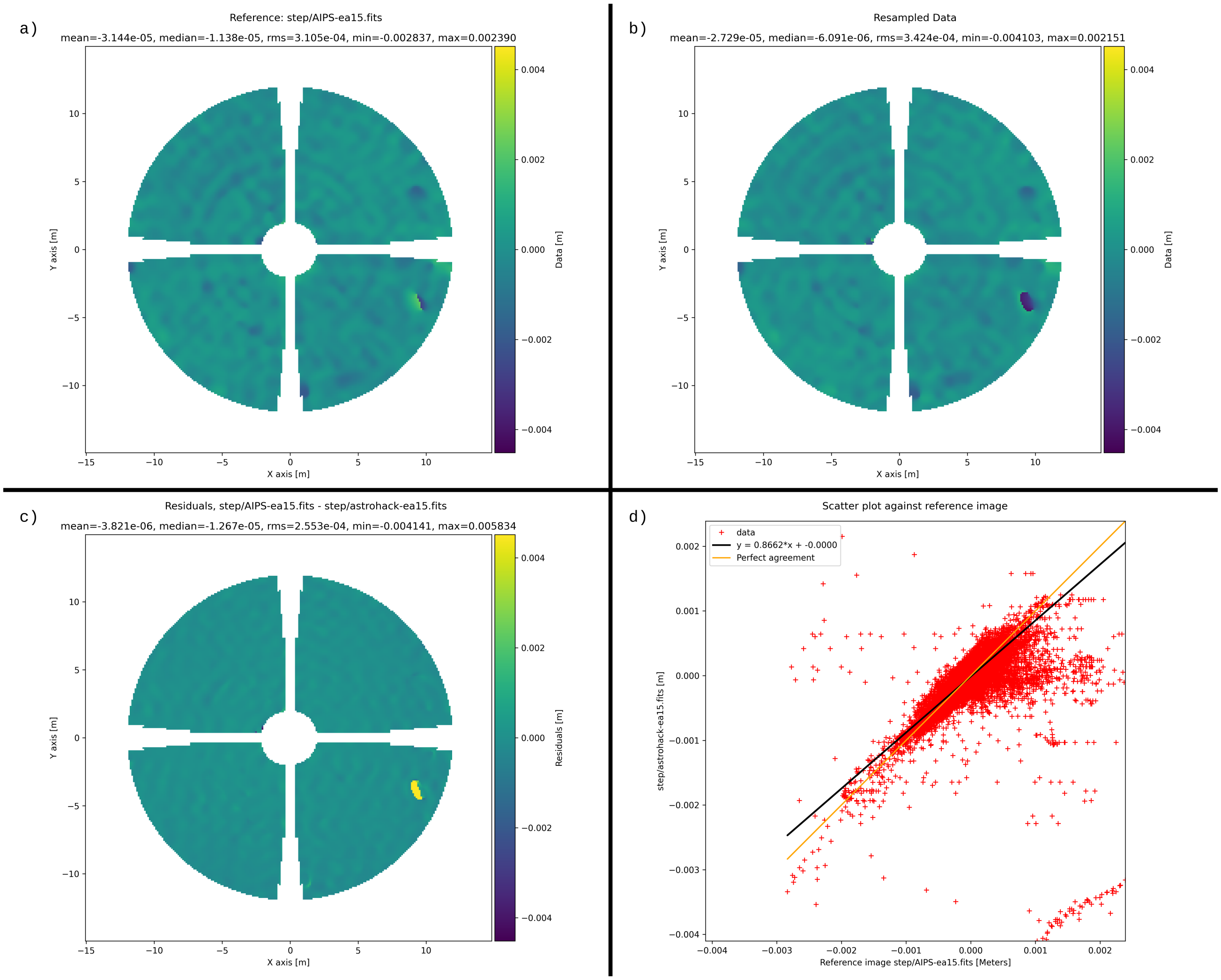


Figure 7: Point & shoot holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA15: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

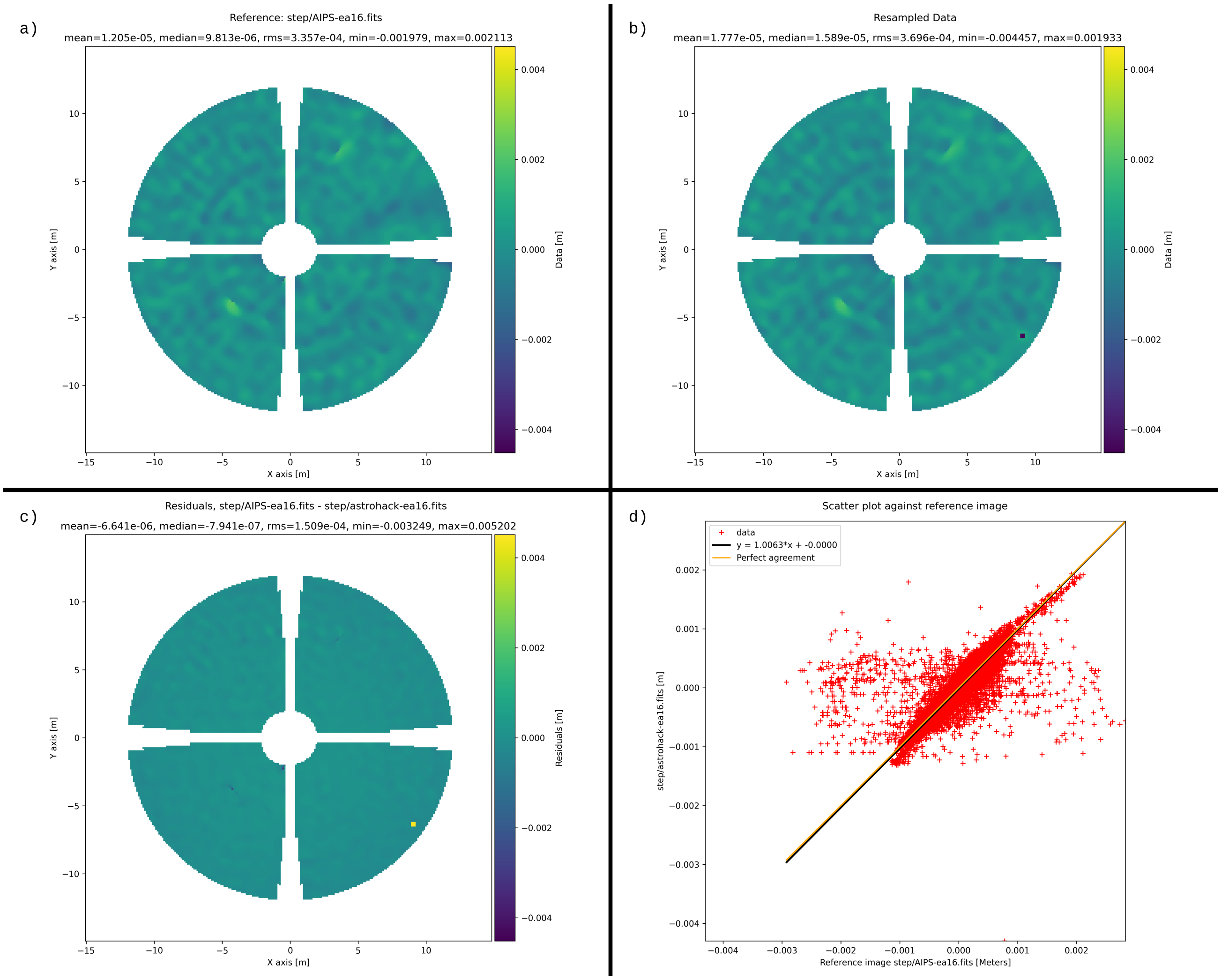


Figure 8: Point & shoot holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA16: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

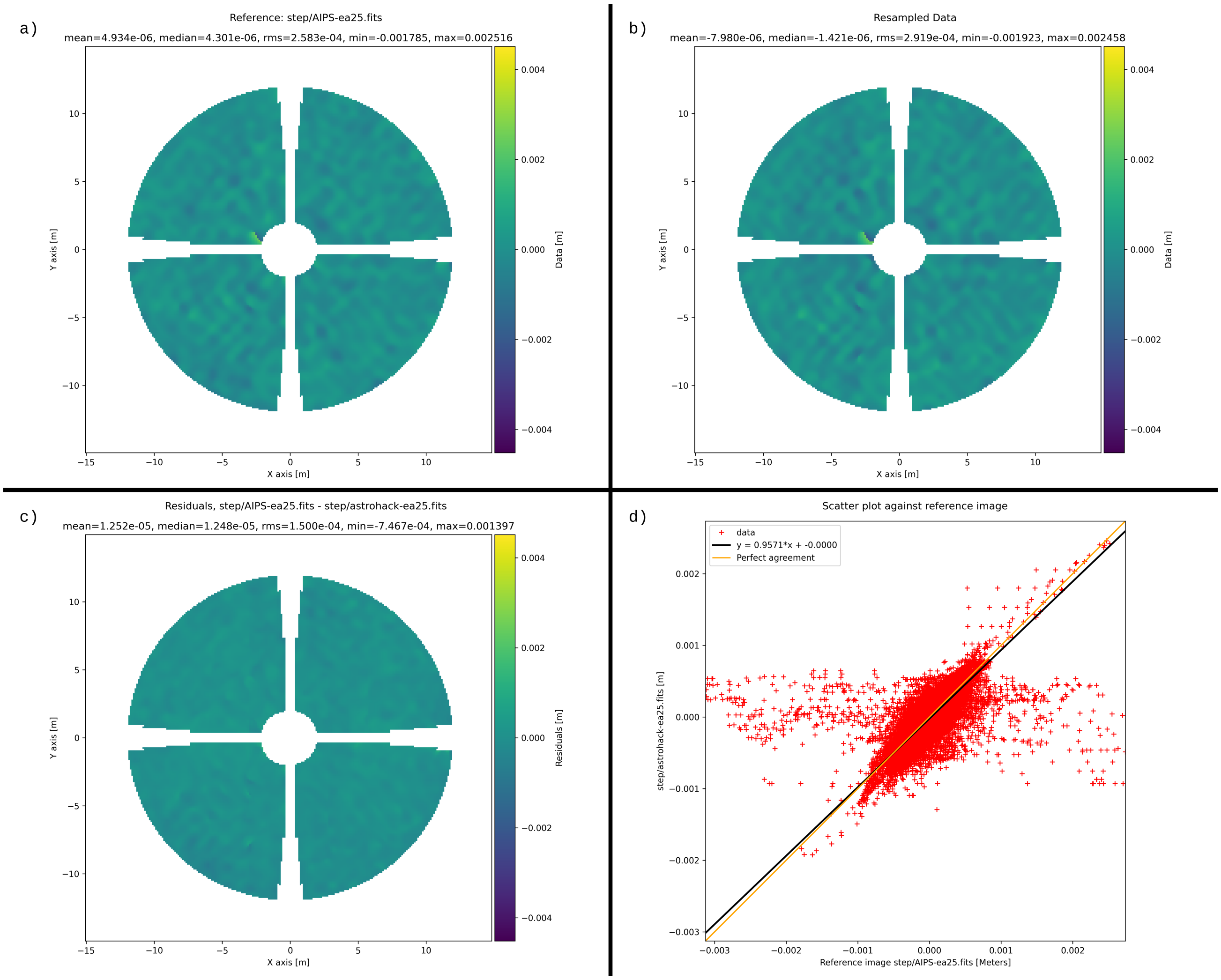


Figure 9: Point & shoot holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA25: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

B OTF surface deviation map comparison

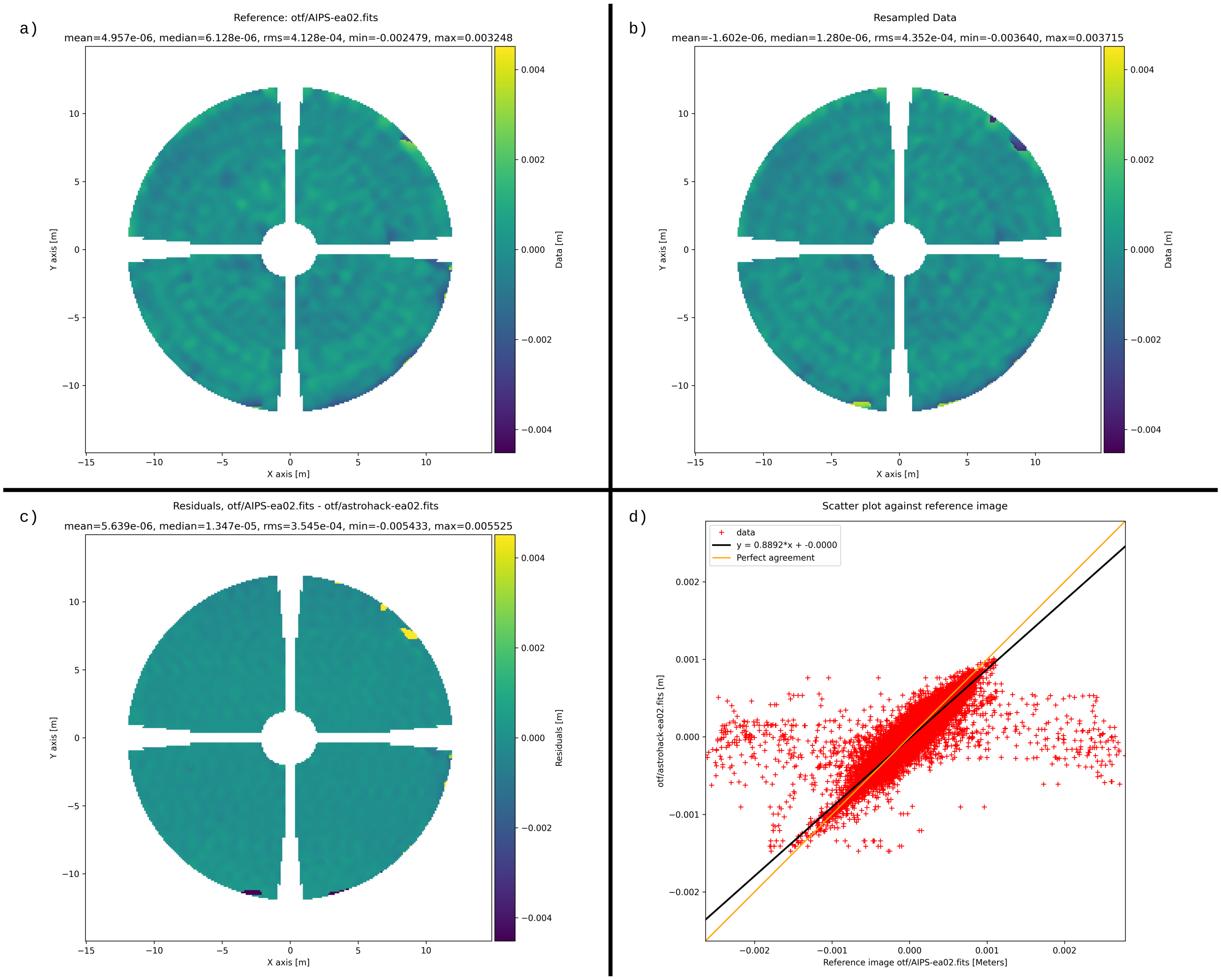


Figure 10: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA02: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

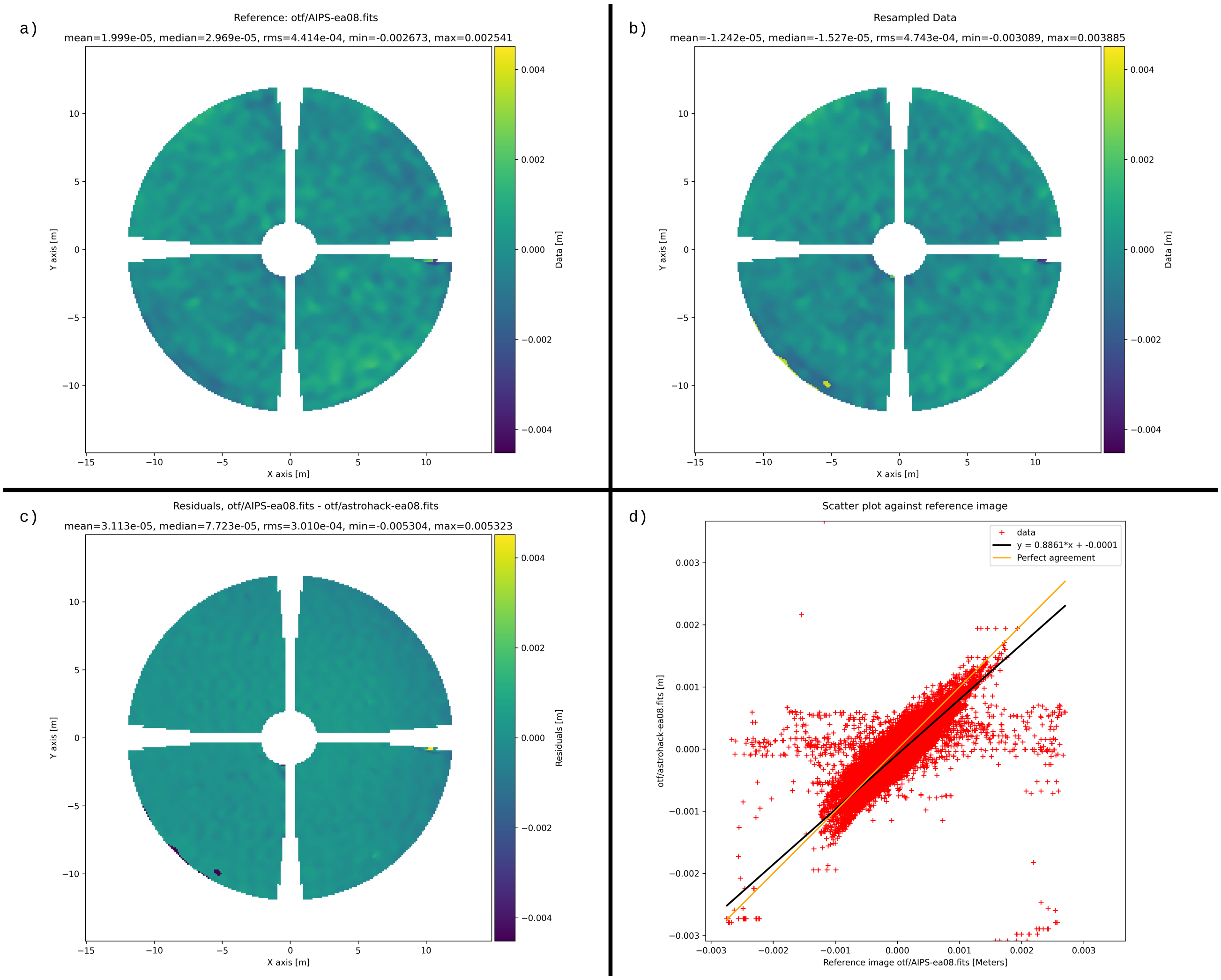


Figure 11: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA08: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

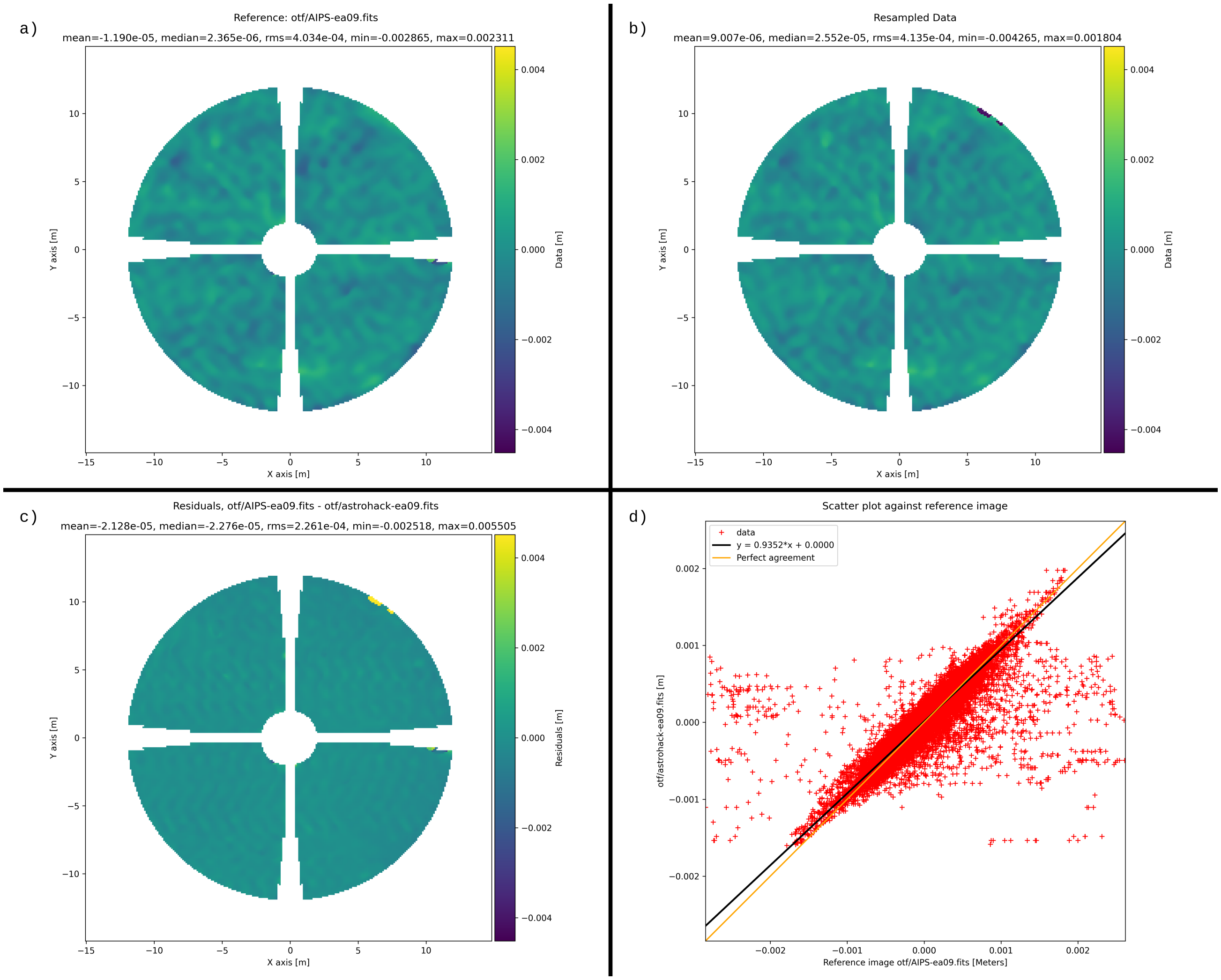


Figure 12: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA09: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

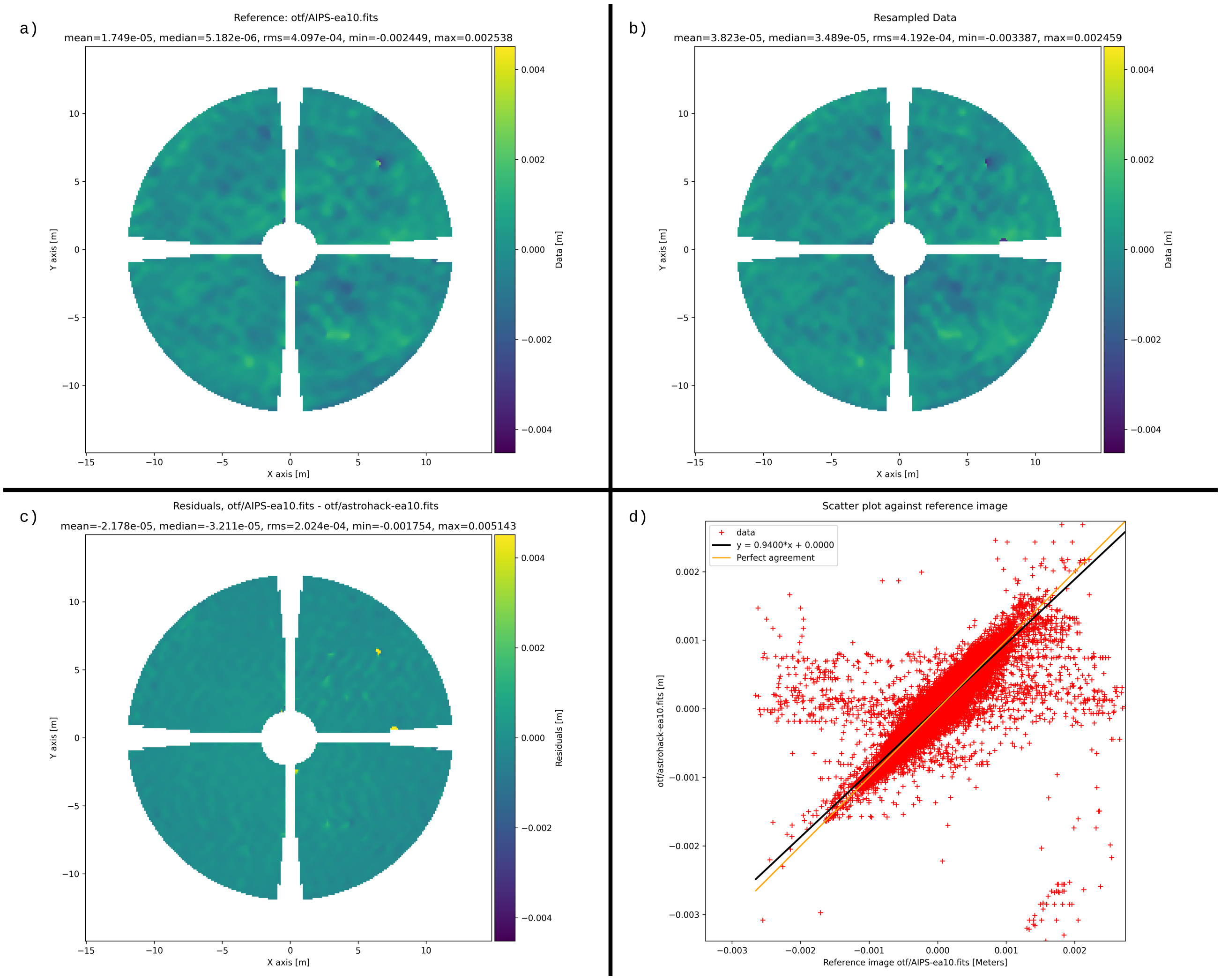
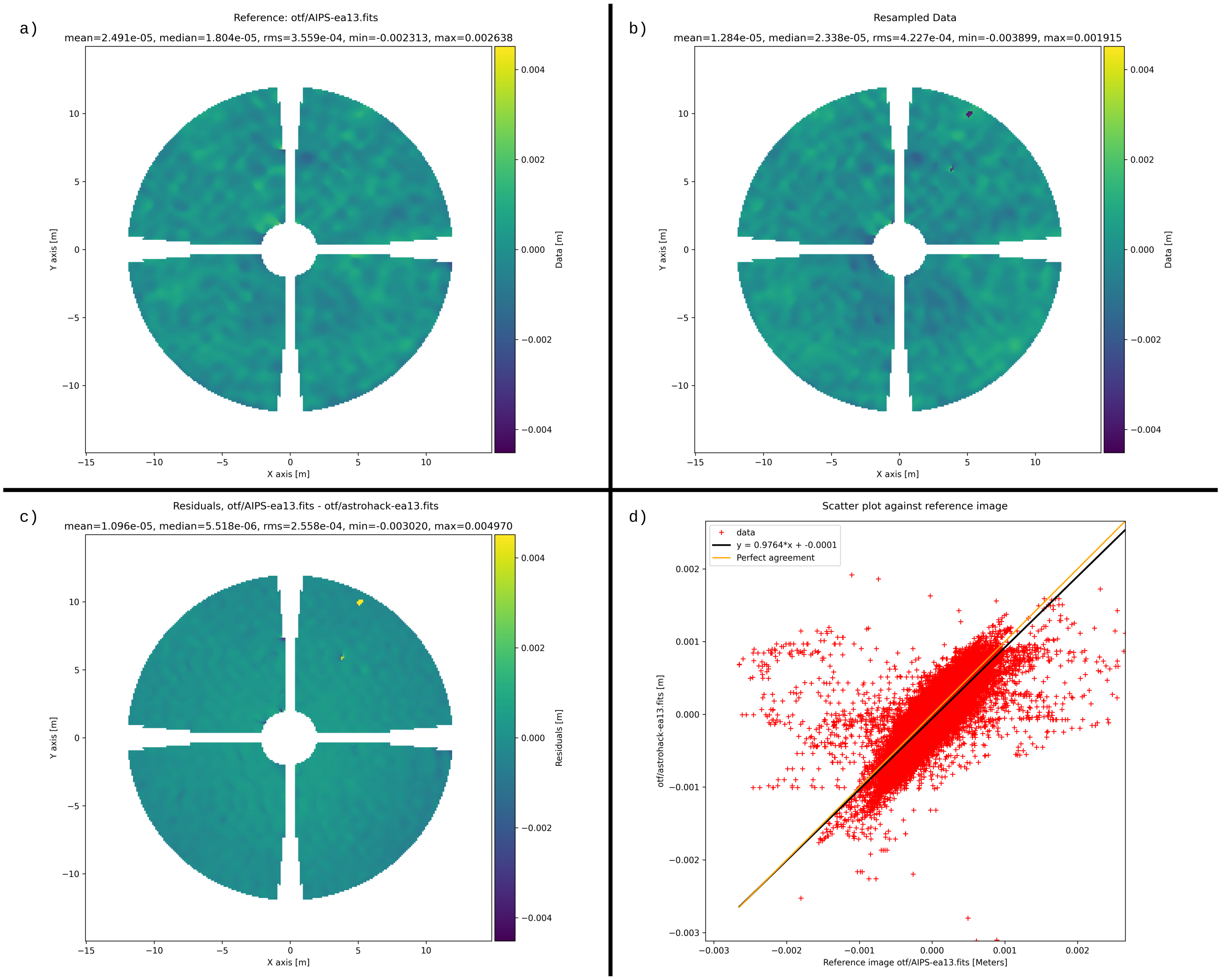


Figure 13: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA10: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).



a) Reference: otf/AIPS-ea13.fits

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b) Resampled Data

mean=1.284e-05, median=2.338e-05, rms=4.227e-04, min=-0.003899, max=0.001915

c) Residuals, otf/AIPS-ea13.fits - otf/astrohack-ea13.fits

mean=1.096e-05, median=5.518e-06, rms=2.558e-04, min=-0.003020, max=0.004970

d) Scatter plot against reference image

Figure 14: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA13: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

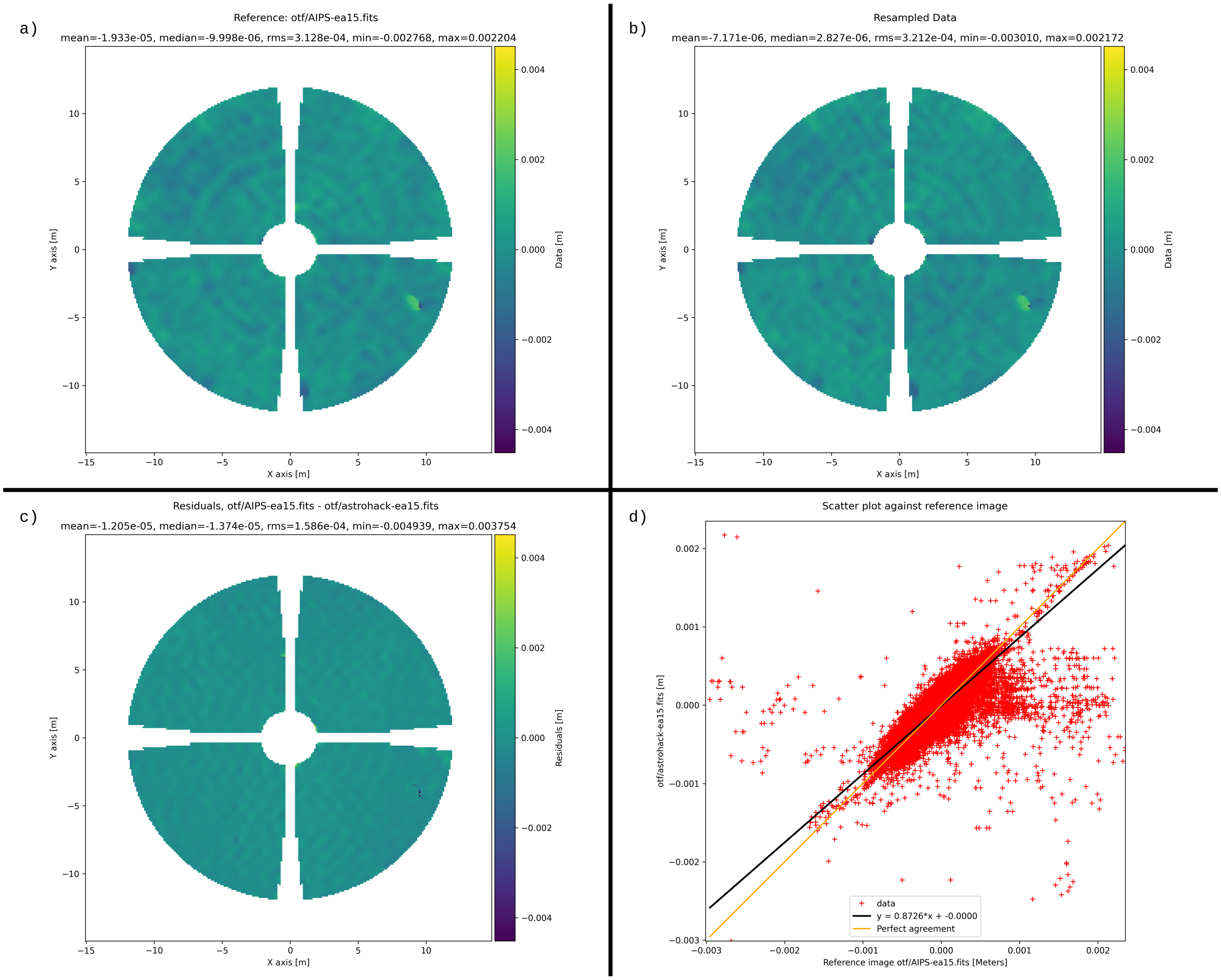


Figure 15: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA15: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

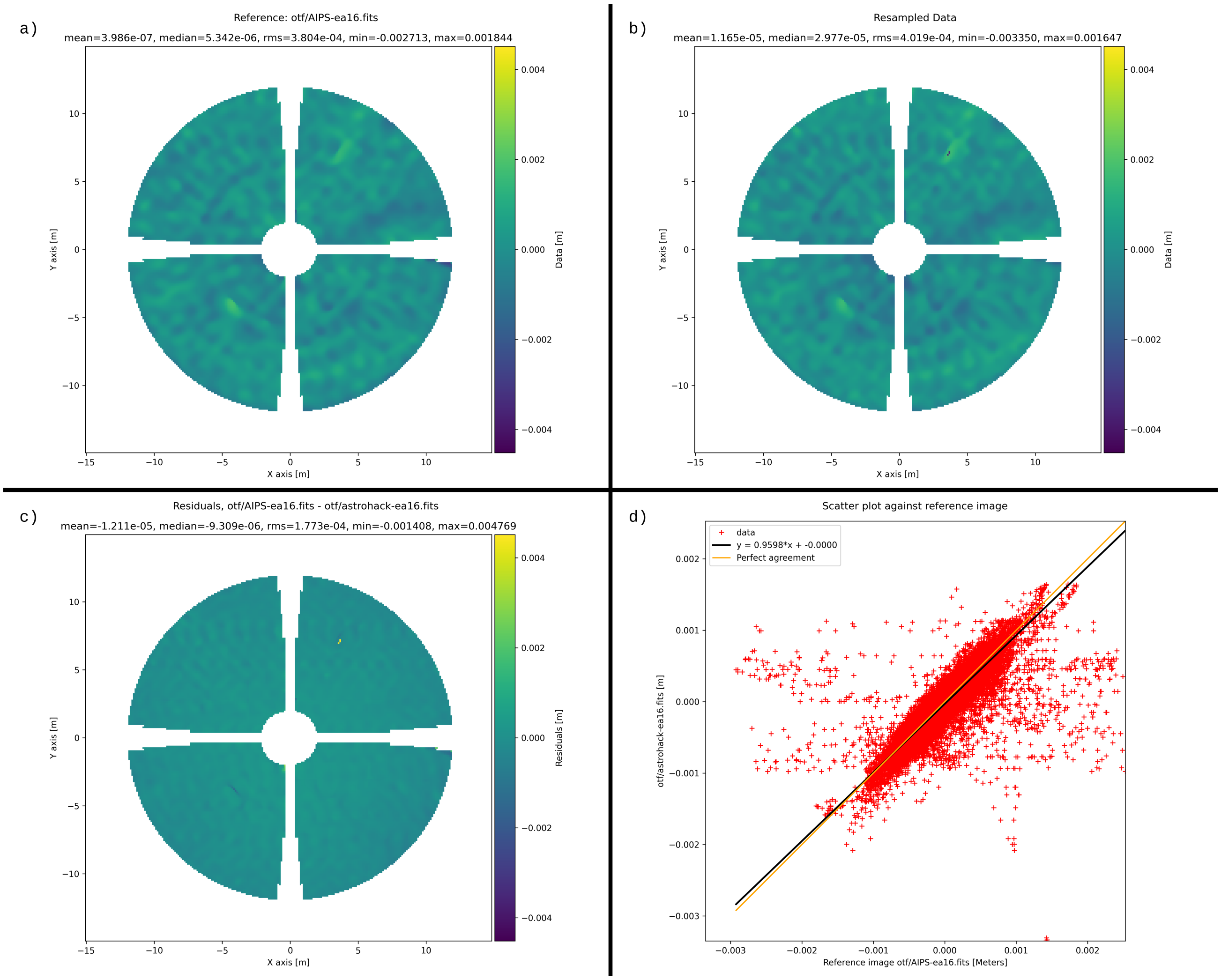


Figure 16: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA16: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

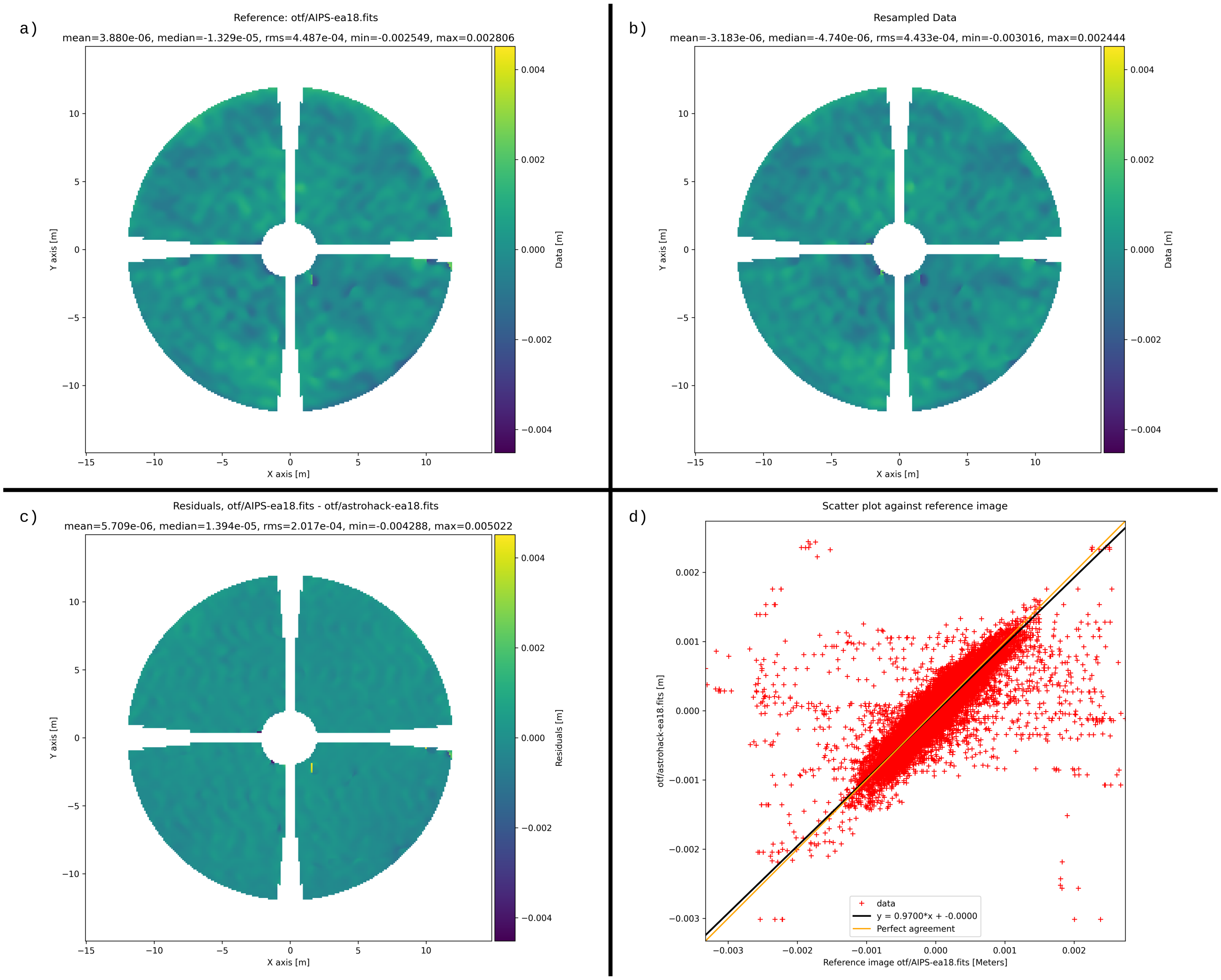


Figure 17: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA18: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

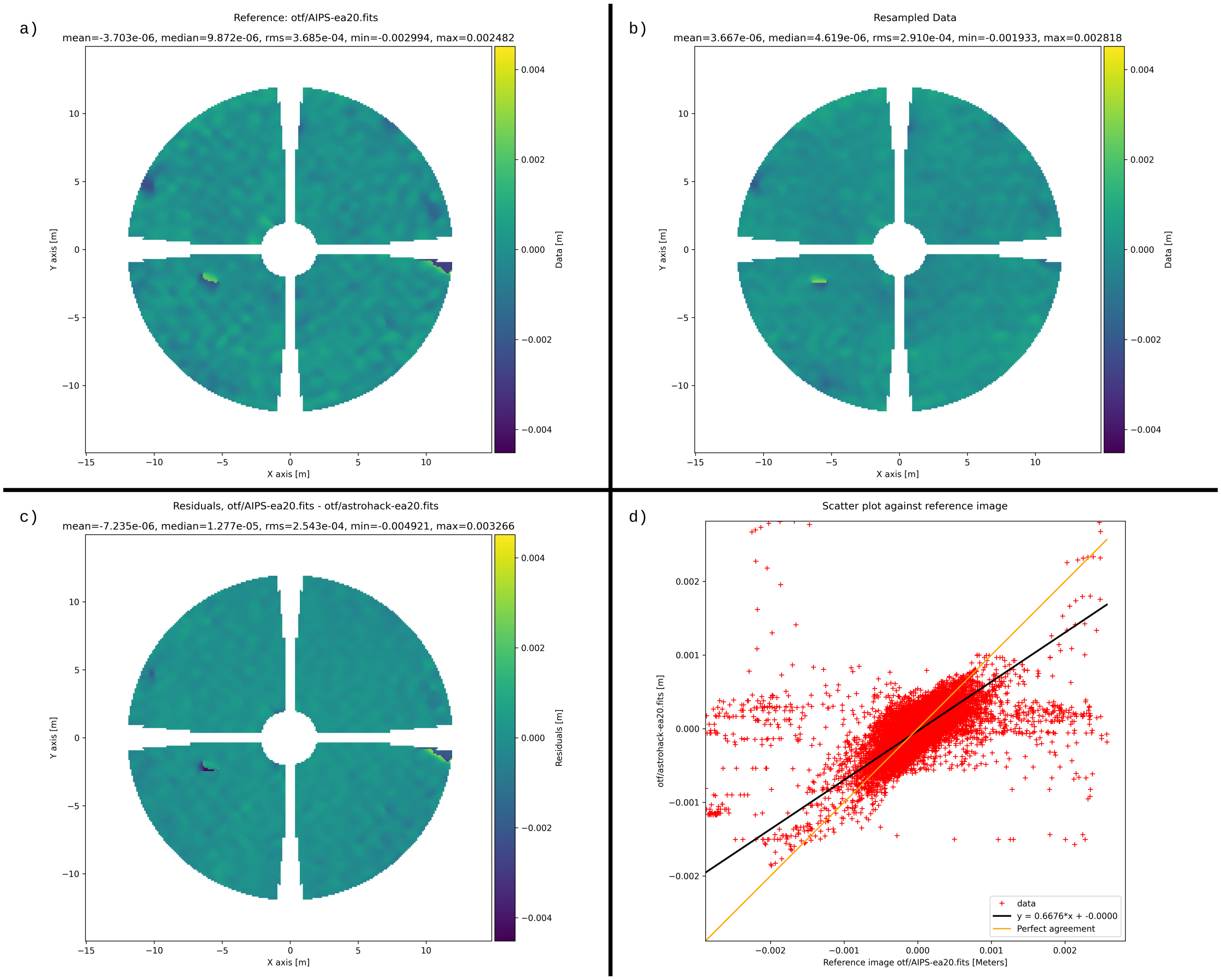
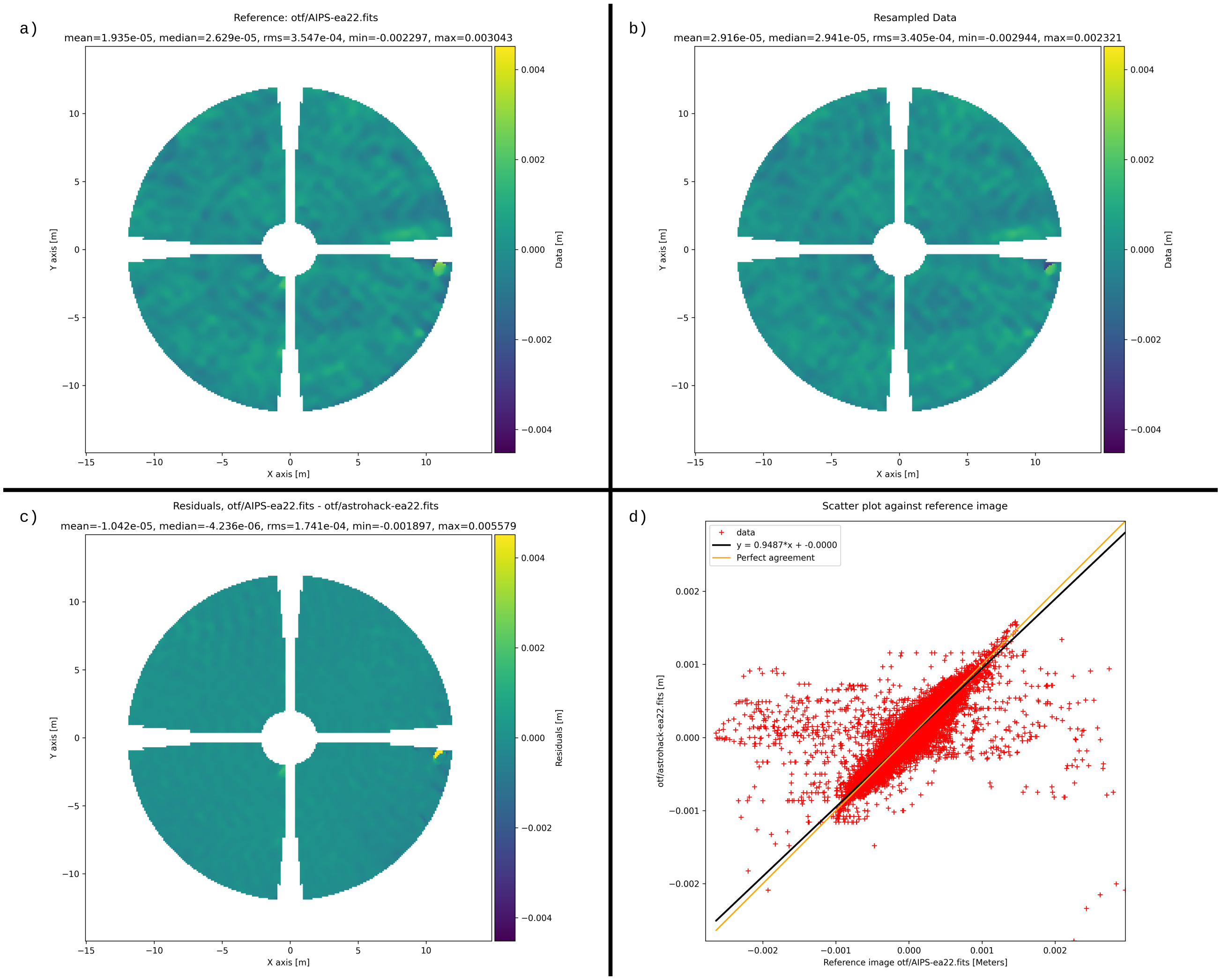


Figure 18: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA20: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).


a) Reference: otf/AIPS-ea22.fits

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b) Resampled Data

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c) Residuals, otf/AIPS-ea22.fits - otf/astrohack-ea22.fits

mean=-1.042e-05, median=-4.236e-06, rms=1.741e-04, min=-0.001897, max=0.005579

d) Scatter plot against reference image

Figure 19: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA22: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

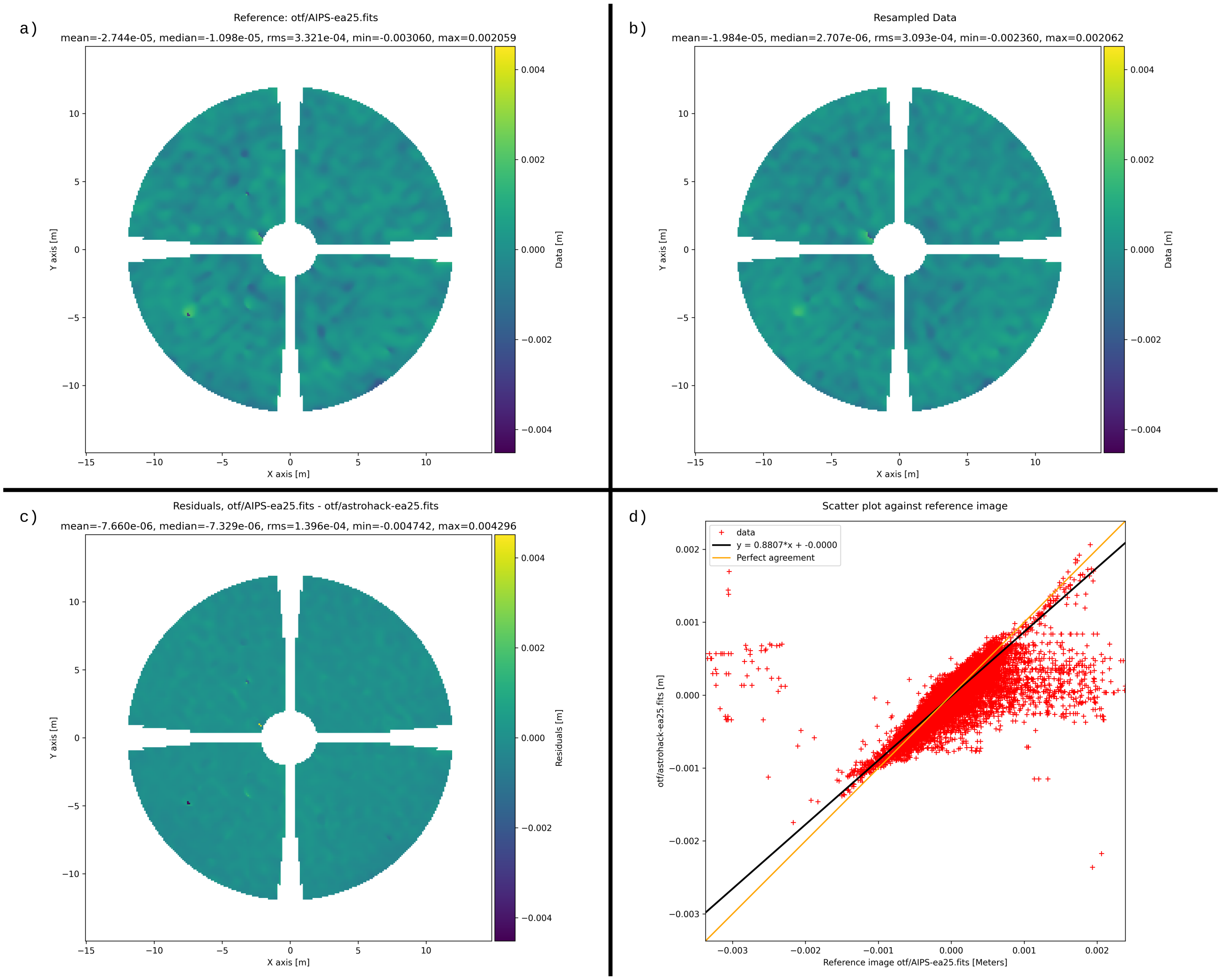

Figure 20: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA25: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).

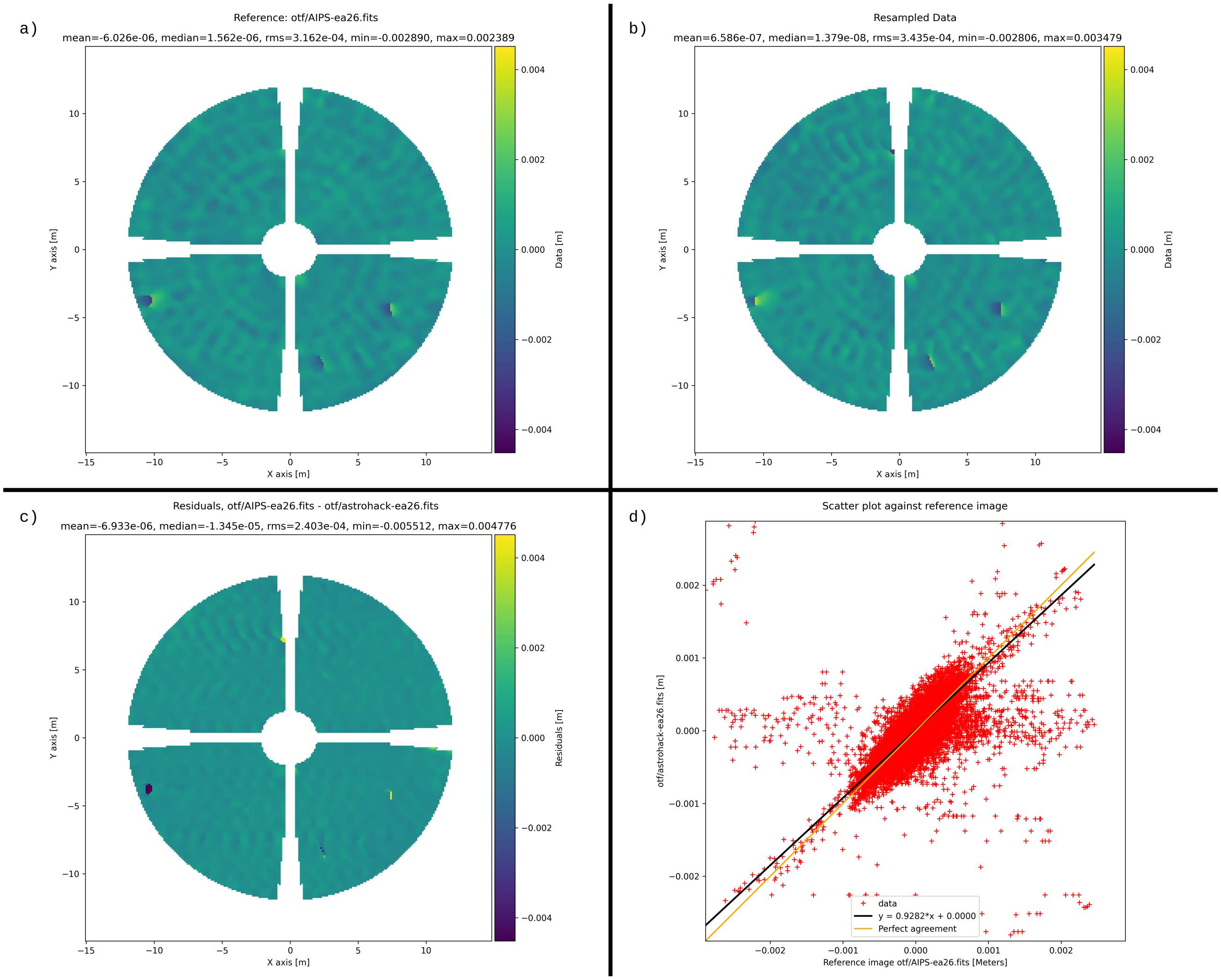

Figure 21: OTF holographic surface deviation map comparison between AIPS and AstroHACK for VLA antenna EA26: a) Reference AIPS map; b) Resampled AstroHACK map to the AIPS map grid; c) Residuals map of the difference between the reference and resampled maps; d) Scatter plot between the reference and resampled maps. Color scale in all images goes from -0.5λ to 0.5λ ($\lambda \approx 9\ mm$).