FEASIBILITY OF DIRECTLY MEASURING SINGLE LINE-OF-SIGHT GPS SIGNAL DELAYS

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1. Executive Summary

The scientific goal of this project is to determine whether it is possible to measure, and with what accuracy, a single line-of-sight[1] GPS signal delay. In this report, we conclude the following:

- The standard method [*Alber et al.*, 2000] for obtaining slant wet delays from GPS double-difference postfit residuals has significant problems because the approach spreads the anisotropic signals over all parameters estimated in the least-squares step and therefore over all reconstructed GPS slant wet delays, causing significant systematic errors.

- Using this standard method, the magnitude of the error in reconstructing slant wet delays is commensurate with the size of the anisotropic signal that we are trying to measure.

- We find the standard method leads to improvements in the root-mean-square (RMS) error of reconstructed slant wet delays of ~10%. This improvement is not a valid measure of algorithm performance since the algorithm leads to significant errors in the reconstructed slant wet delays.

- The accuracy of the standard method would be improved if there were external constraints on the atmospheric parameters estimated in the least-squares step. However, the GPS approach would be unnecessary if such independent constraints were available.

[1] Line-of-sight, slant path, one-way, and ray are used interchangeably in this report.

2. Project Goal

The Global Positioning System (GPS) can provide measurements of water-vapor delays integrated along the vertical direction with a precision of a few millimeters from simultaneous observations to about a dozen GPS satellites. For atmospheric applications such as weather forecasting and climate monitoring, however, information about the vertical distribution of moisture, not just the vertically integrated moisture, is considerably more desirable. Recent simulations indicate that it may be possible to retrieve the three-dimensional distribution of moisture in the atmosphere if accurate measurements of integrated water vapor along the GPS receiver-to-satellite line-of-sight, also known as the slant wet delays, were available [*MacDonald et al*., 2002]. However, the slant path GPS signal delay is neither a pure observable nor an estimated parameter. The slant path delay is currently reconstructed by combining atmospheric parameter estimates (i.e., zenith delay and gradient parameters) with postfit phase residual information. For example, *Alber et al*. [2000] and *Braun et al*. [2001] have developed and used a method to obtain slant wet delays by unwrapping GPS double-differenced postfit phase residuals. In making all these reconstructions, a series of accumulated approximations are necessary.

The scientific goal of this project is to determine whether it is possible to measure, and with what accuracy, a single line-of-sight GPS signal delay. To accomplish this goal we have adopted the following three-step approach: (1) review and assess existing methods, (2) develop new method(s) and, (3) validate results. We report here on (1) by using simulated observations for a realistic GPS network, whereby we explore the impact of some of these approximations to estimate their effect on the accuracy of recovered slant path delays. In particular, we have objectively and rigorously assessed the feasibility of the method of *Alber et al*. [2000] for retrieving unambiguous slant wet delays from GPS double-difference postfit residuals.

3. Appendices

In the appendix, we include the following illustrative series of simulations that demonstrate the conclusions presented above:

- Simulation of a perfectly homogeneous atmosphere. (We define a perfectly homogeneous atmosphere as one that can be characterized (i.e., parameterized) by a zenith delay and gradient parameter.) This simulation serves the double purpose of introducing and validating the various components involved in our simulations.

- Simulation of a perfectly homogeneous atmosphere but for an anisotropy along a single slant path. This simulation serves to illustrate (1) the magnitude of the error in reconstructing slant wet delays and, (2) the RMS error improvement of reconstructed slant wet delays using the standard method.

- Same as last above but with atmospheric parameters tightly constrained to their true value. This simulation serves to illustrate the use of external constraints on the atmospheric parameters estimated in the least-squares approach to improve the standard method.

We also include other simulations for different atmospheric and observational conditions to further demonstrate the conclusions presented.

4. References

Alber, C., R. Ware, C. Rocken, J. Braun, "Obtaining single path phase delays from GPS double differences", *Geophys. Res. Lett., 27(17)*, 2661-2664, 2000.

Braun, J., C. Rocken, R. Ware, "Validation of line-of-sight water vapor measurements with GPS", *Radio Sci., 36(3)*, 459-472, 2001.

MacDonald, A. E., Y. Xie, R. H. Ware, "Diagnosis of three-dimensional water vapor using a GPS network", *Mon. Wea. Rev., 130*, 386-397, 2002.

5. Acknowledgments

This work was supported by NOAA/FSL contract RA1330-02-SE-0221. J. Braun of UCAR provided us with the site coordinates used in the simulations.

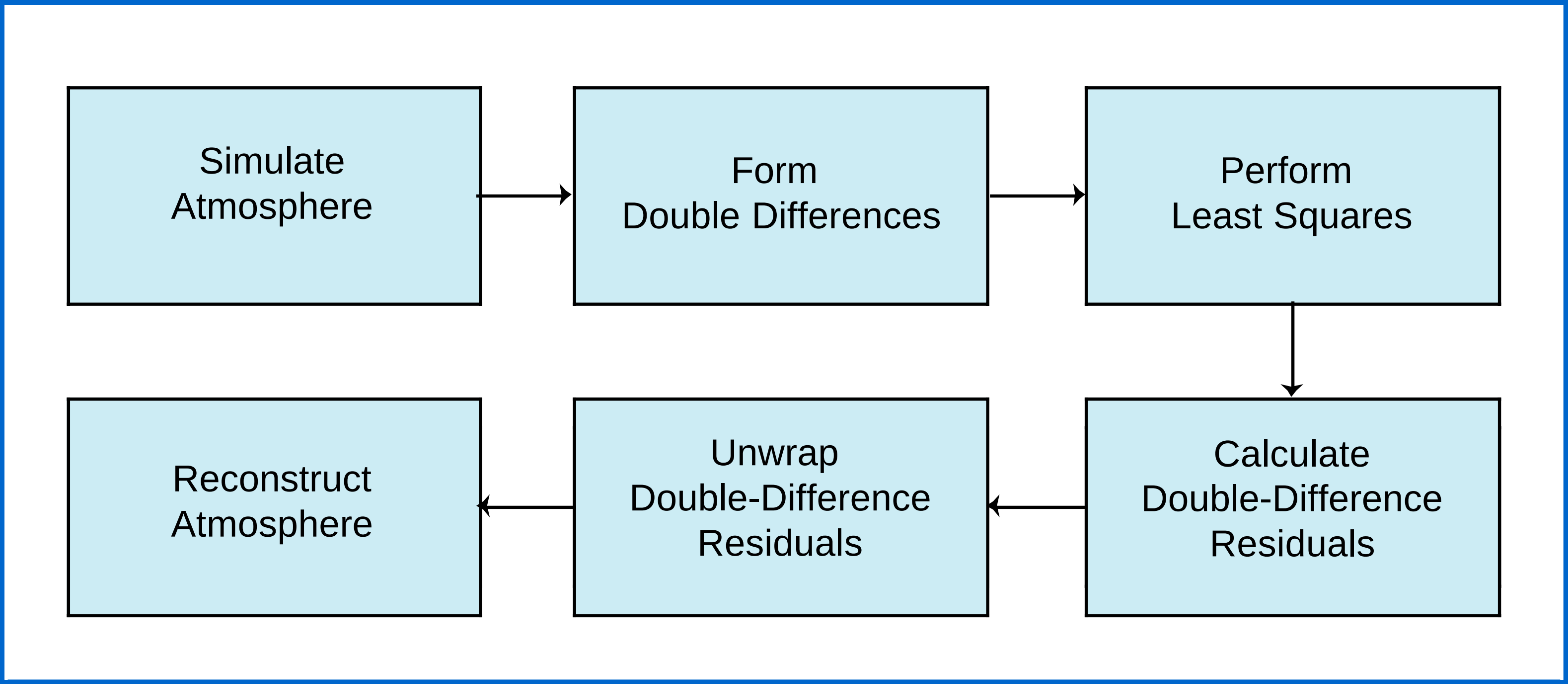
Appendix

We will first introduce the GPS simulator that we have developed to assess the feasibility of the standard method [*Alber et al.*, 2000] for obtaining slant wet delays from GPS double-difference postfit residuals, and then present a series of simulations that demonstrate that this standard method has significant problems.

Conclusions

- All reconstructed slant wet delays using the standard method result in significant errors.
- The errors introduced by the standard method are commensurate with the magnitude of the anisotropy signal that we are trying to measure.
- Given these errors, the small improvement in the RMS error of reconstructed slant wet delays using the standard method is not a valid measure of algorithm performance.
- The accuracy of the standard method would be improved if external constraints on atmospheric parameters were available.

GPS Simulator



Components of the simulator that we have developed to assess the standard method for obtaining slant wet delays from GPS double-difference postfit residuals. In the approach adopted, we simulate one-way phase observations for a specific atmosphere, form double-difference phases from the simulated one-way observations, use least squares to estimate atmospheric (and other relevant) parameters, calculate double-difference residuals, unwrap them, and reconstruct one-way phase observations.

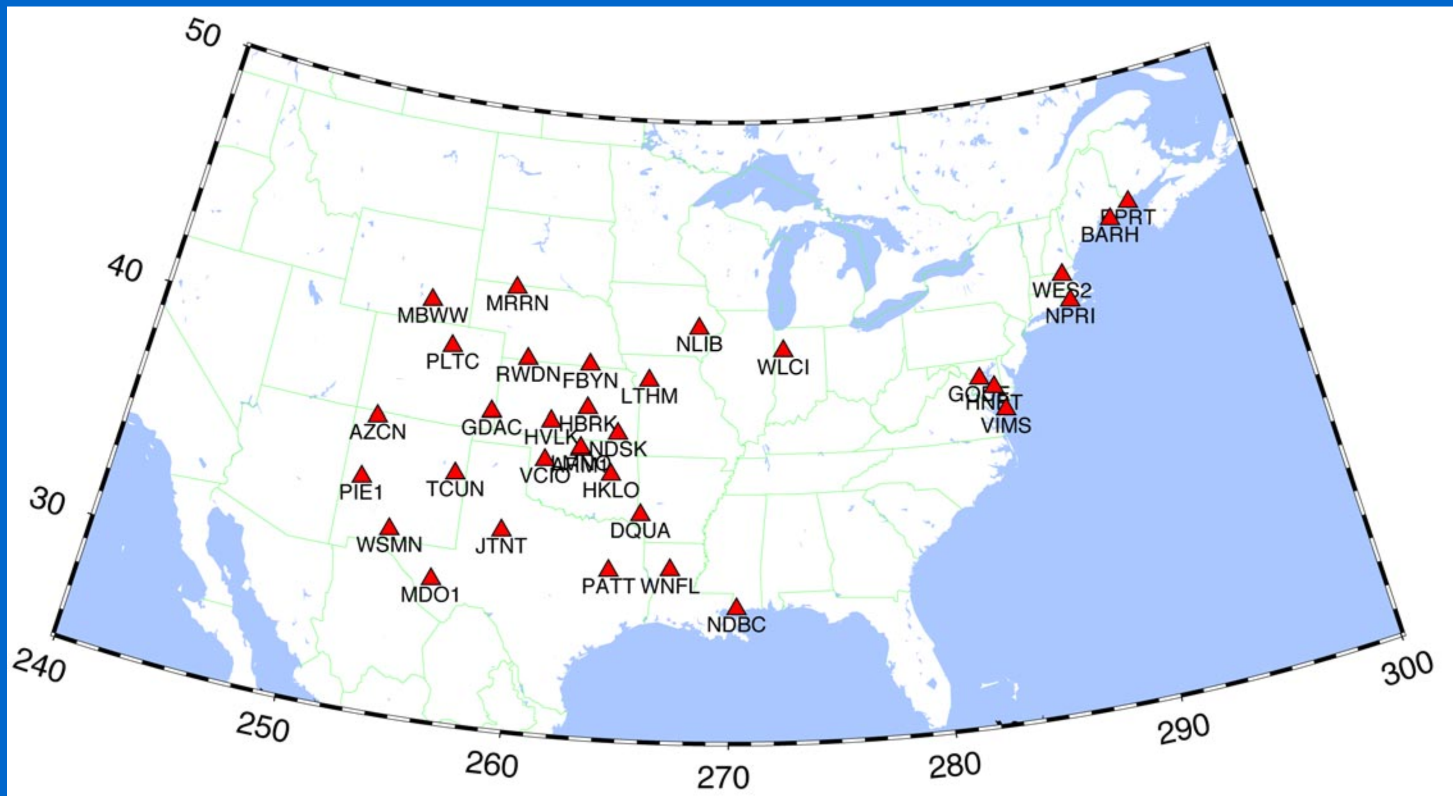
Overview of Simulations

- We have performed a series of simulations, which we will introduce in turn.

- In all the simulations:
  - The observing system is perfectly calibrated, i.e., the simulated one-way phase observations are free of multipath, scattering, ionospheric, tropospheric, satellite orbit and clock, site position and clock, observational or any other GPS error. In other words, the simulated one-way observations are exclusively due to the contribution of pure atmospheric water vapor.

  - The GPS constellation as observed at a 33-site ground-based network spanning the US, with a minimum elevation angle of 10°, defines the geometry.

Ground-based GPS Network



The GPS network consists of 33 sites spanning most of the continental US. The smallest and longest baselines are 9 and 3628 km, respectively, with a quasi-continuous baseline length distribution between them. This network was used by *Braun et al.* [2003] to compare GPS- and WVR-derived slant wet delays at the Atmospheric Radiation Measurement (ARM) Program’s central facility near Lamont, OK. (Site coordinates provided by J. Braun of UCAR.)

Series of Simulations

- Homogenous atmosphere, i.e., atmosphere at each site perfectly characterized (parameterized) by a zenith delay and gradient parameters

- Same as I except for a single anisotropy at one satellite-site pair

- Same as II except that the atmospheric parameters are tightly constrained to their true value.

I

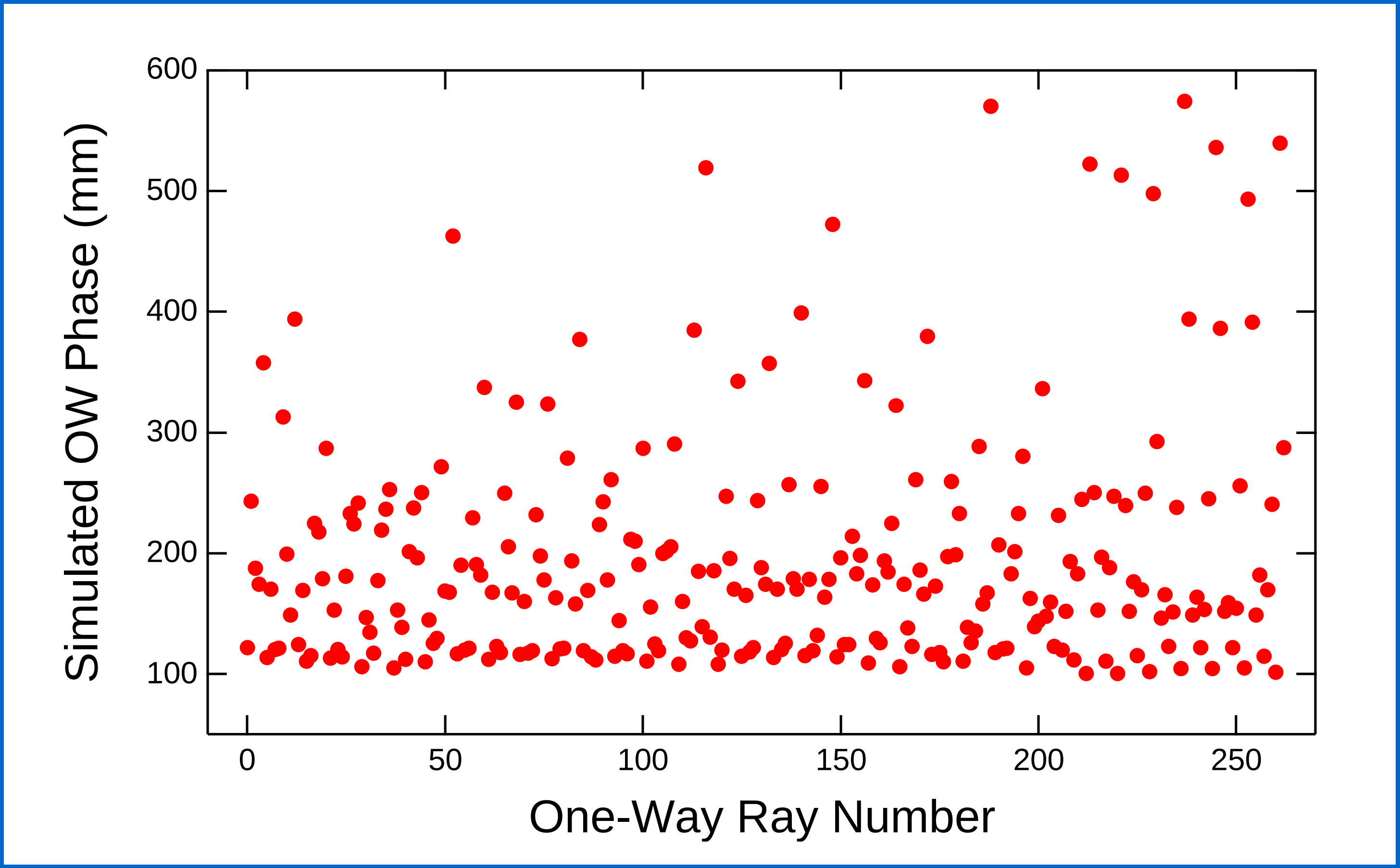
Simulation I

Homogenous atmosphere: simulated atmosphere at each site perfectly parameterized by a zenith delay and gradient parameters.

This simulation serves the double purpose of introducing and validating the various components involved in our simulations.

Simulate Atmosphere

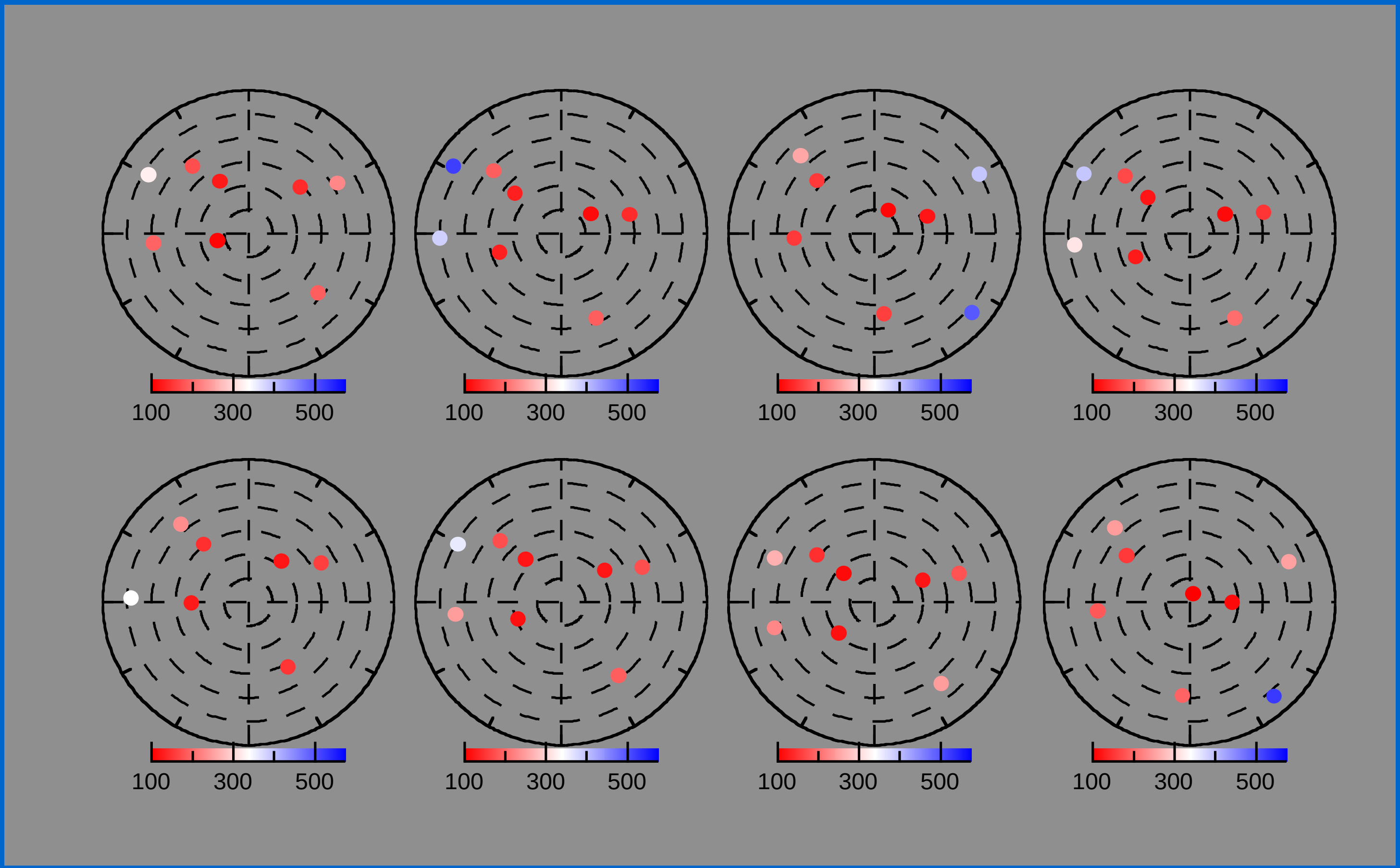
I



Simulated atmosphere characterized by 100 mm of zenith delay and a NE (45° direction) gradient of 0.3 mm magnitude at zenith (equivalent to ±10 mm at 10° elevation angle) for all one-way phases. There are 263 (approximately 8 satellites per site times 33 sites) phases. In general, small phase values correspond to high-elevation satellites and vice versa.

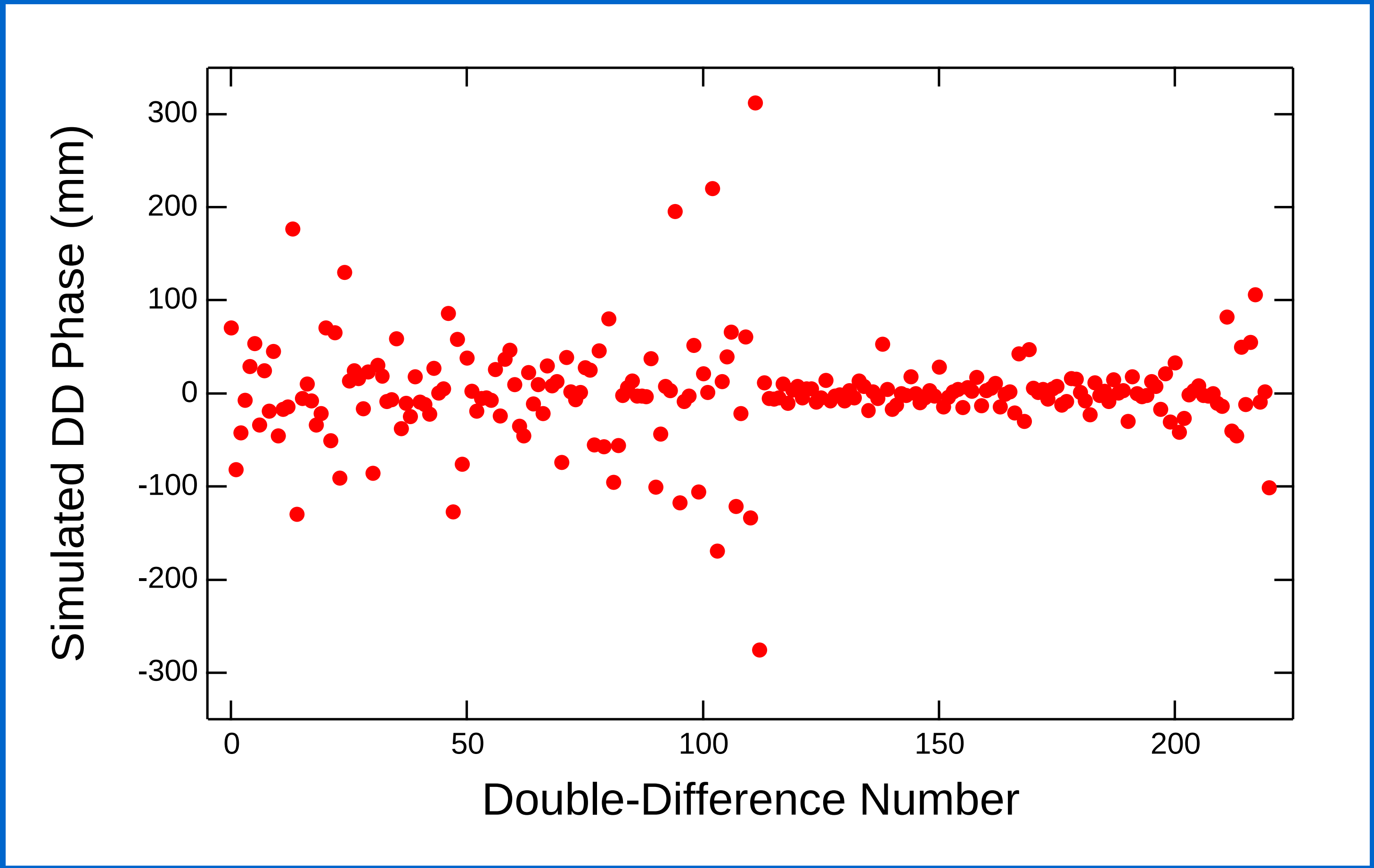
Simulate Atmosphere

I



Sky plot representation of simulated atmosphere for, from left to right and from top to bottom, sites MDO1, WLCI, VIMS, ARM1, NDBC, LMNO, MRRN, and BARH. Up is north, left is west, outer circumference is the horizon, and center is zenith. Colors represent one-way phase values in mm.

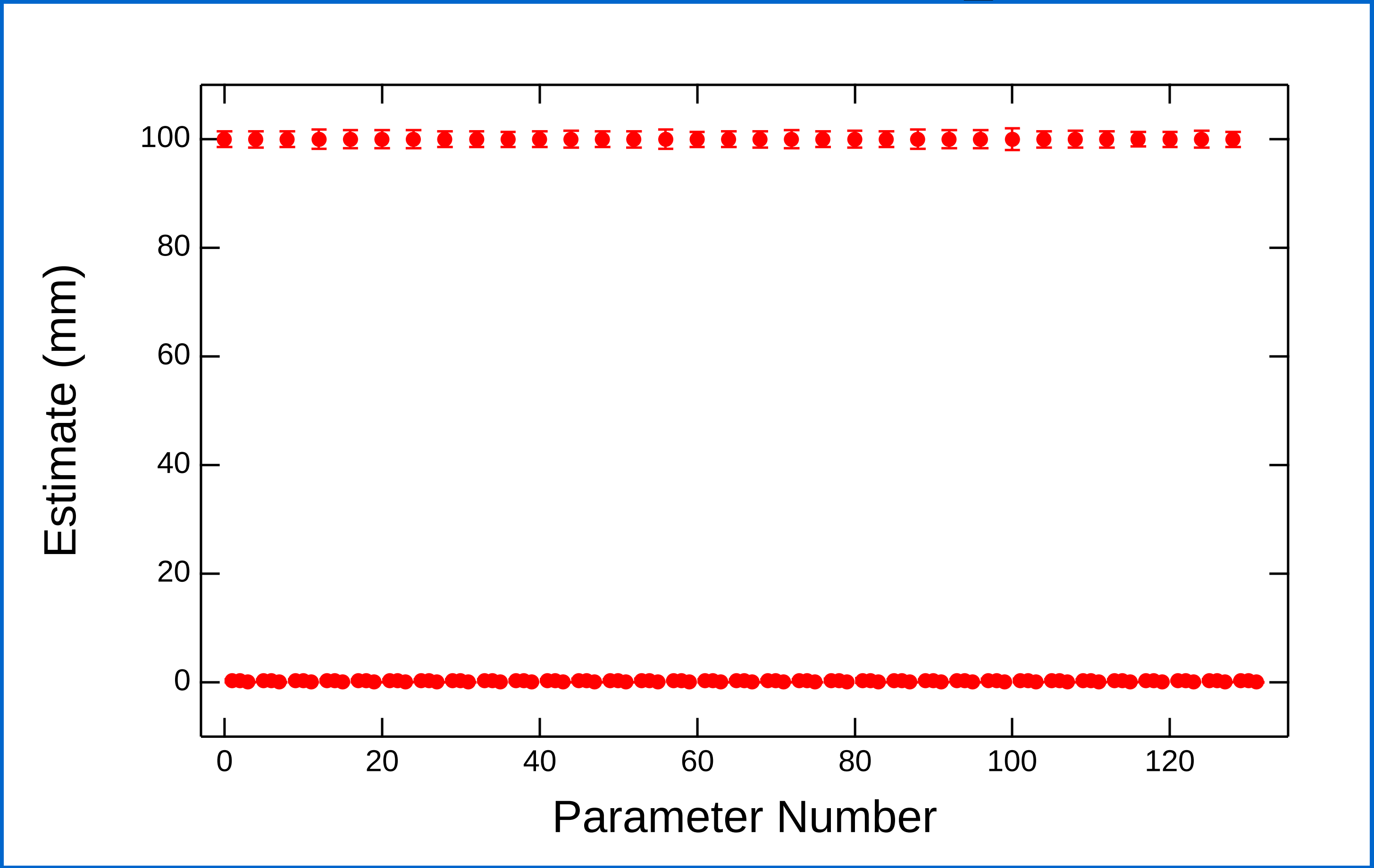
Form Double Differences



Simulated atmosphere results in 221 independent double-difference phases. In general, small values involve sites that form short baselines and thus observe the same satellites through similar atmospheres. Large values involve longer baselines and satellites with significantly different low-elevation angles.

Perform Least Squares

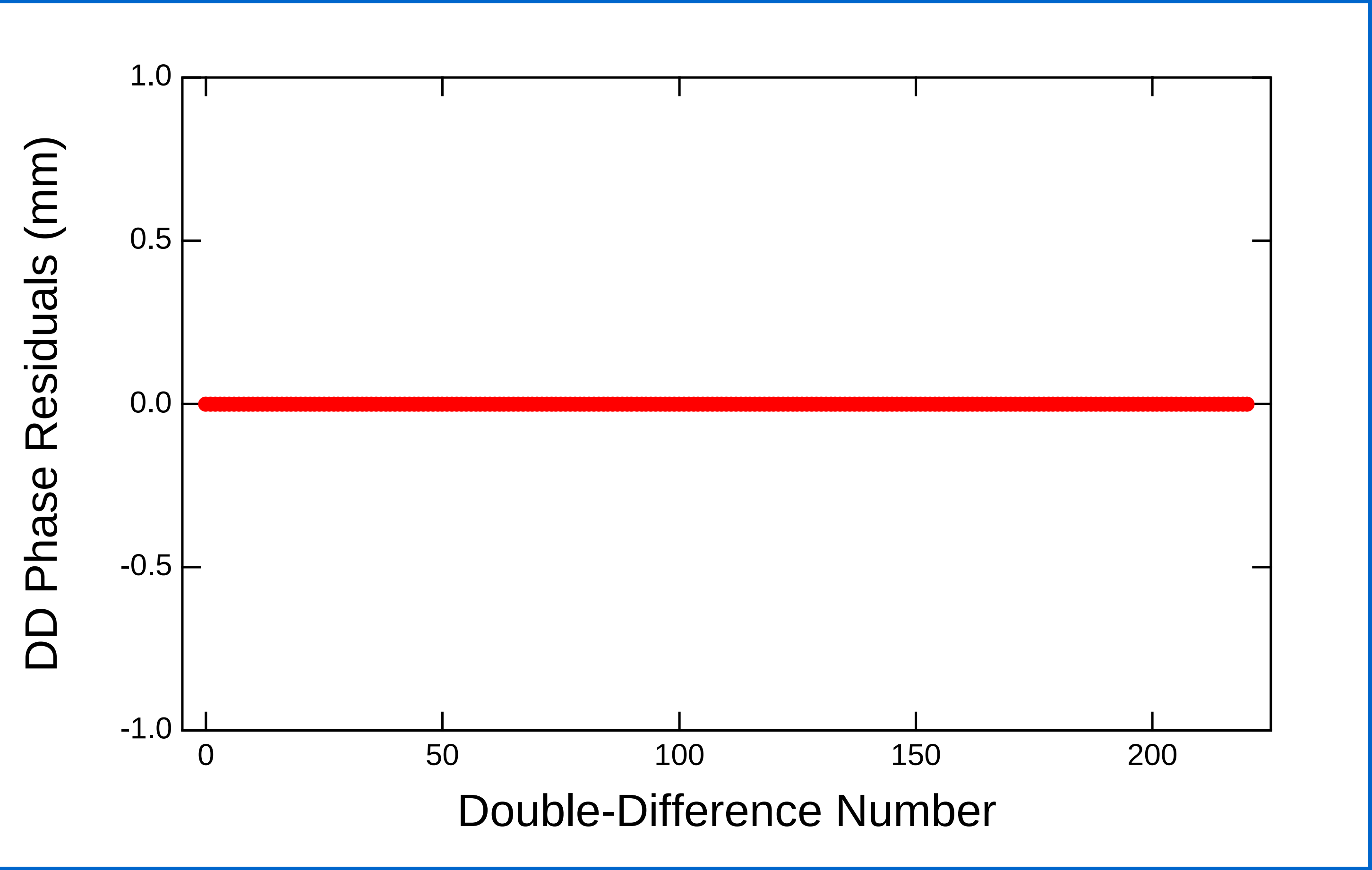
I



Estimate four parameters per site: zenith delay, north and east gradient, and vertical component of site position (the last constrained to zero mm with an uncertainty of 0.001 mm). Least squares estimates the simulated 100 mm zenith delay and 0.3 mm NE gradient parameters at all sites perfectly. Error bars are the 1-σ statistical uncertainties.

Calculate Double-Difference Residuals

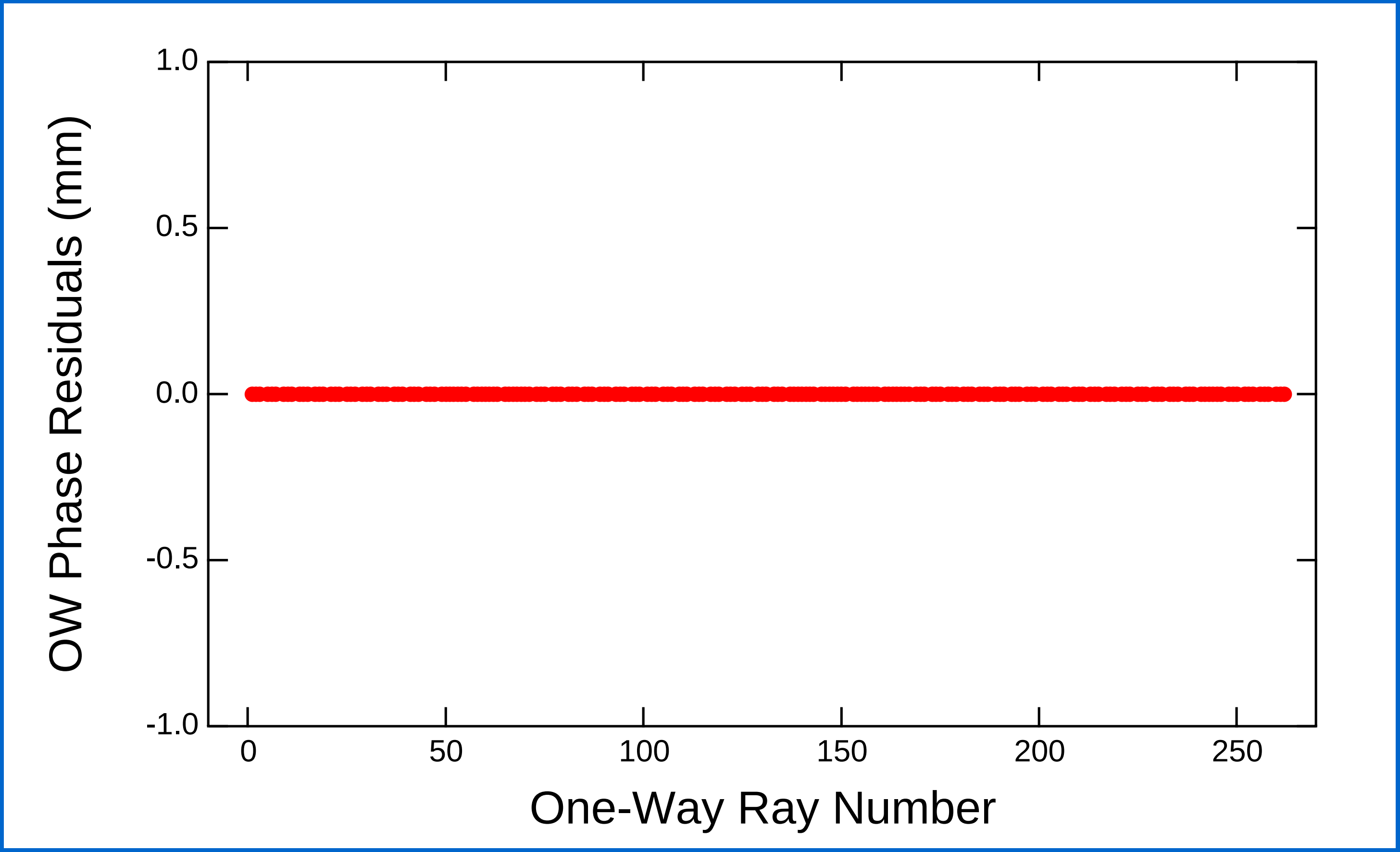
I



Double-difference residuals are all exactly zero mm.

Unwrap Double-Difference Residuals

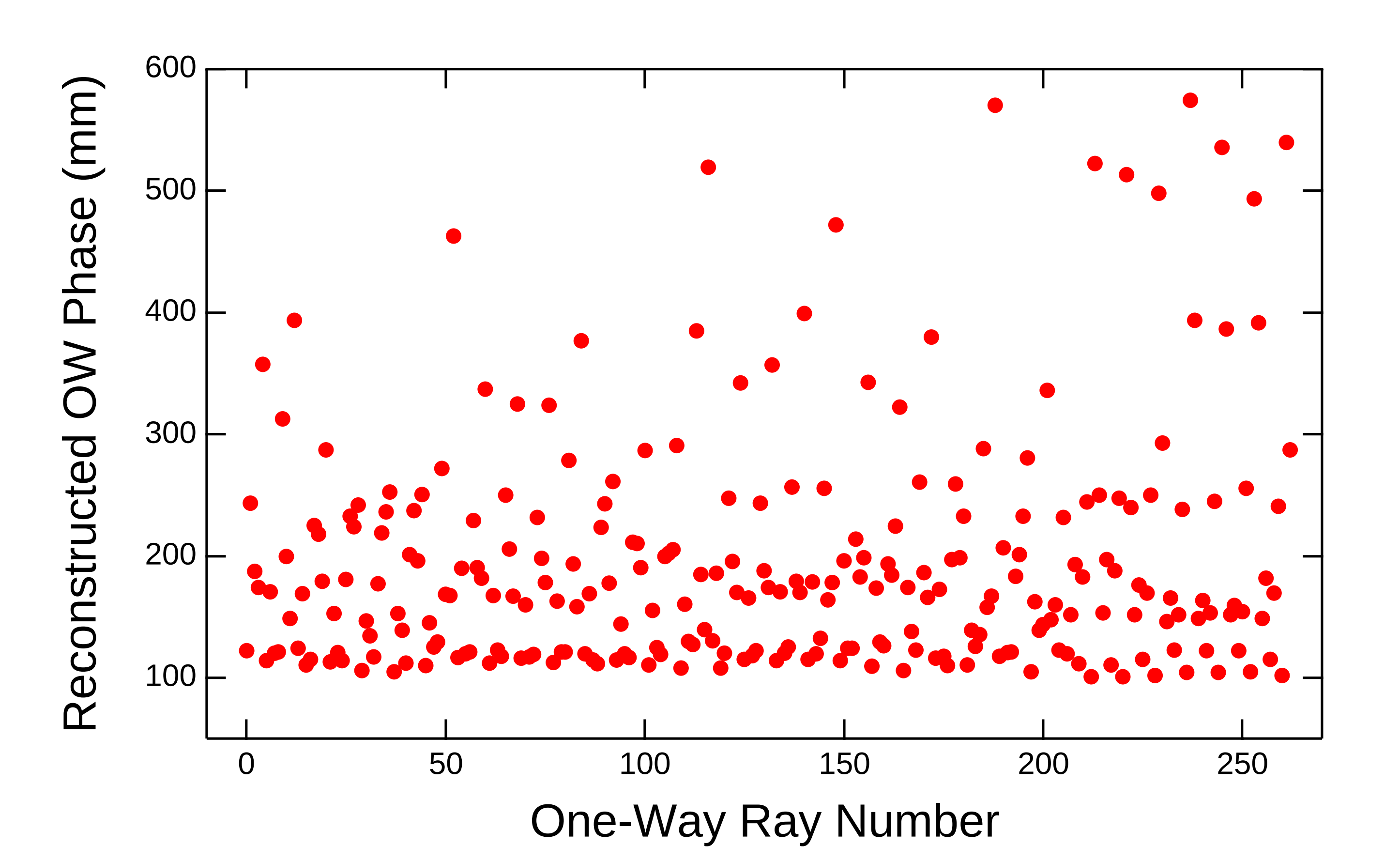
I



Alber et al. [2000] “zero-mean” assumption used for unwrapping the double-difference residuals into one-way phase residuals. All one-way phase residuals are exactly zero mm.

Reconstruct Atmosphere

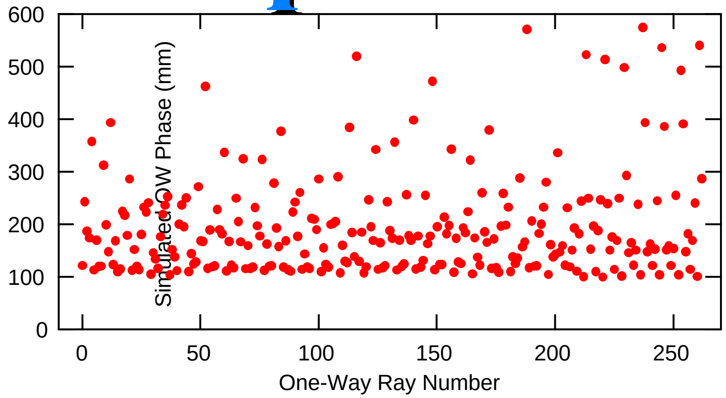
I

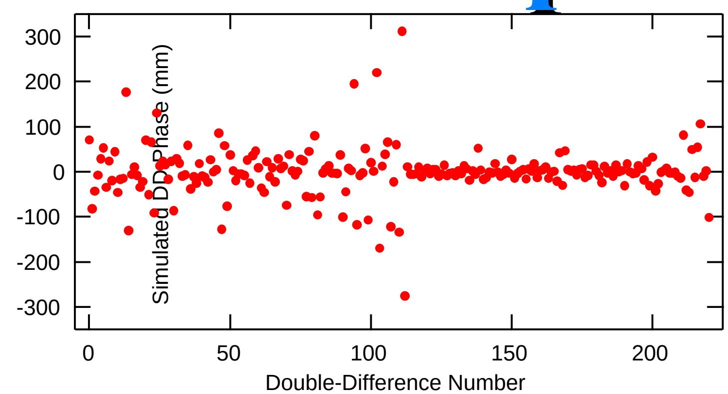


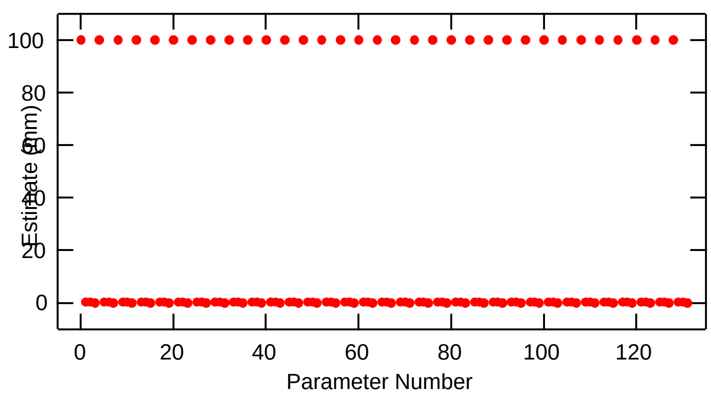
Reconstructed atmosphere is the sum of the estimated atmosphere in the double-difference least-squares solution and the unwrapped one-way phase residuals.

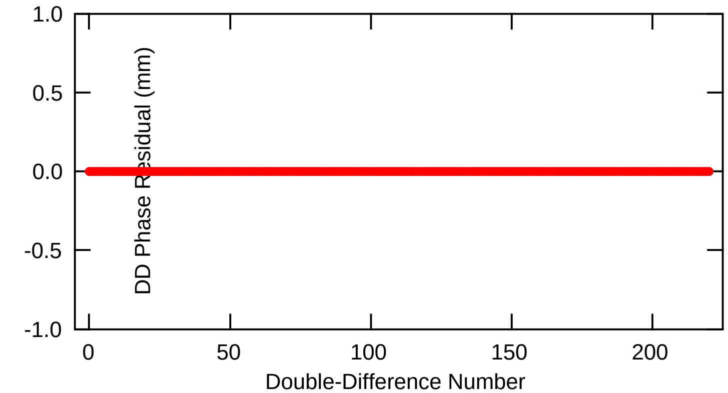
Composite of Previous Graphs

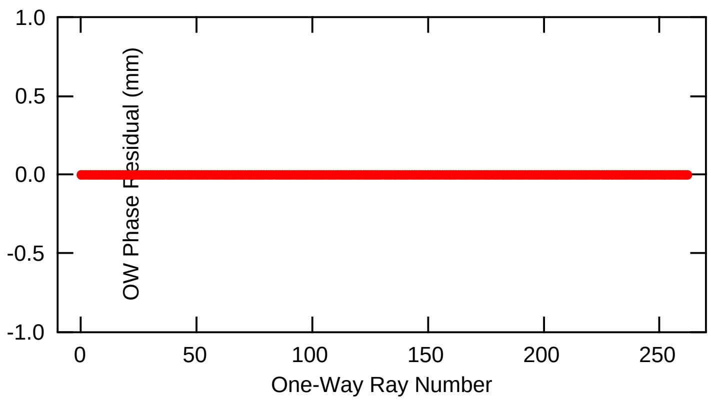
I

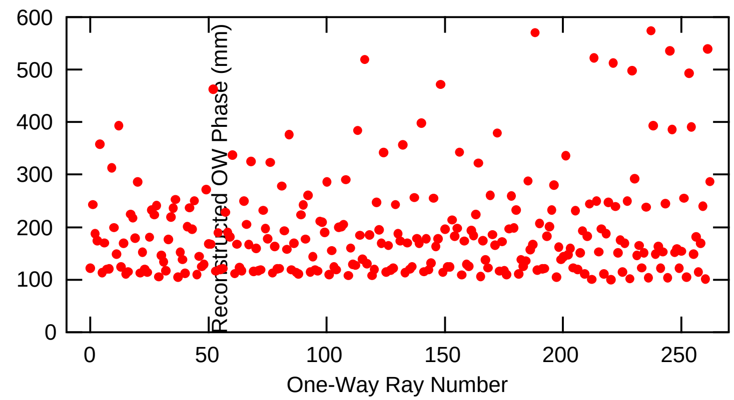






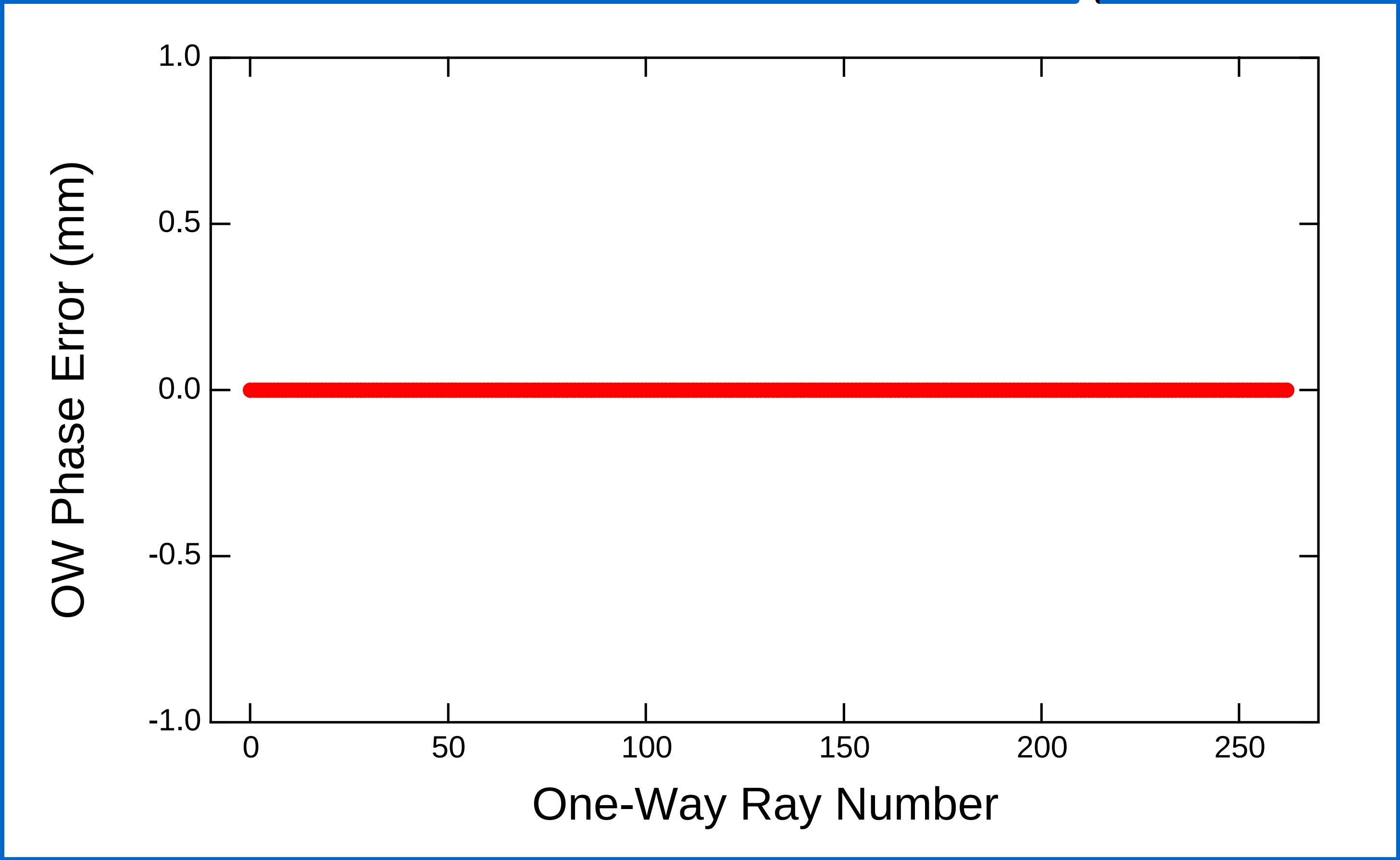






I

Compare Simulated and Reconstructed Atmospheres



The simulated and reconstructed atmospheres are identical and thus their difference is exactly zero mm for all one-way phases.

I

Summary of Simulation I

- Least squares estimates all parameters perfectly.
- For this case, the “zero-mean” is both mathematically and “physically” a correct assumption that produces correct unwrapped one-way phase residuals.
- The simulated and reconstructed atmospheres are exactly identical.
- The various components of the GPS simulator developed are validated.

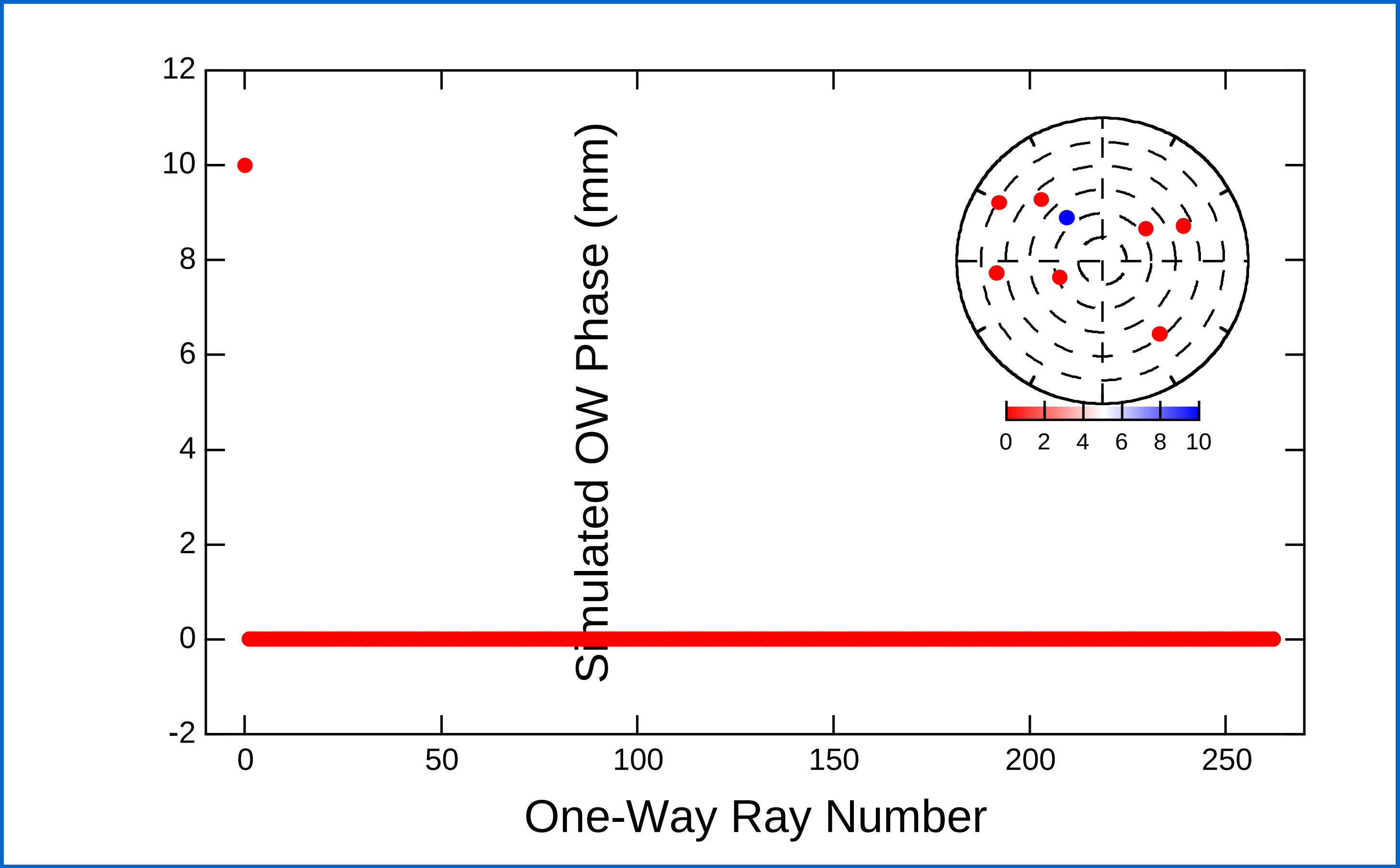
II

Simulation II

Simulated atmosphere is perfectly homogenous but for an anisotropy along a single slant path.

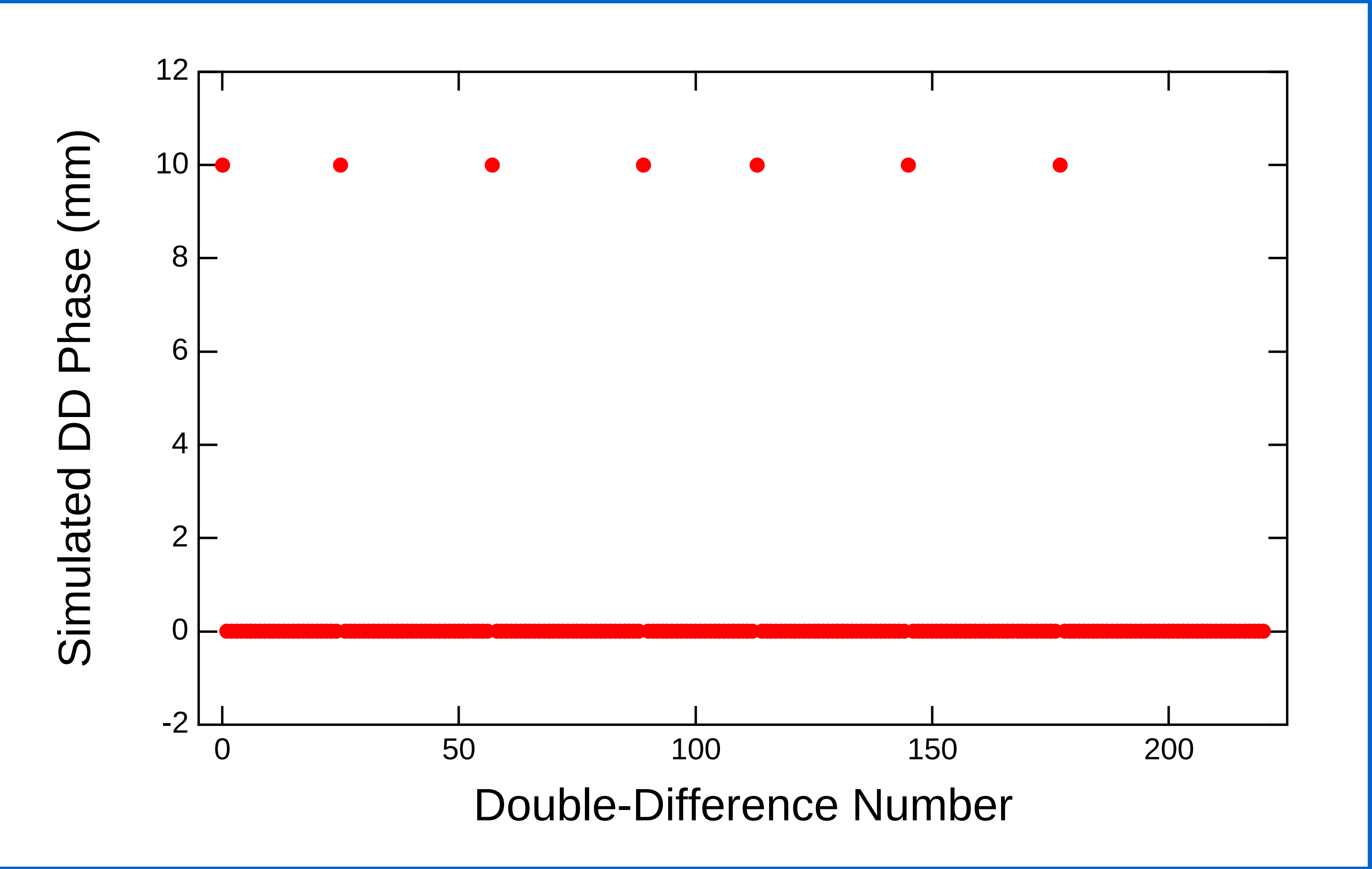
The outcome of the simulation does not depend on the actual values of the simulated parameters because the least-squares model used is linear on these parameters. We will therefore simulate a homogenous atmosphere using zero mm for all zenith delay and gradient parameters to improve visualization.

Simulate Atmosphere



Simulated atmosphere is zero mm for all one-way phases but one (Ray 0; involving a satellite (blue in inset) and site ARM1, a GPS site at the ARM's facility). The anisotropy represented by Ray 0 amounts to 10 mm of one-way phase. Colors in sky plot (inset) represent simulated phase values.

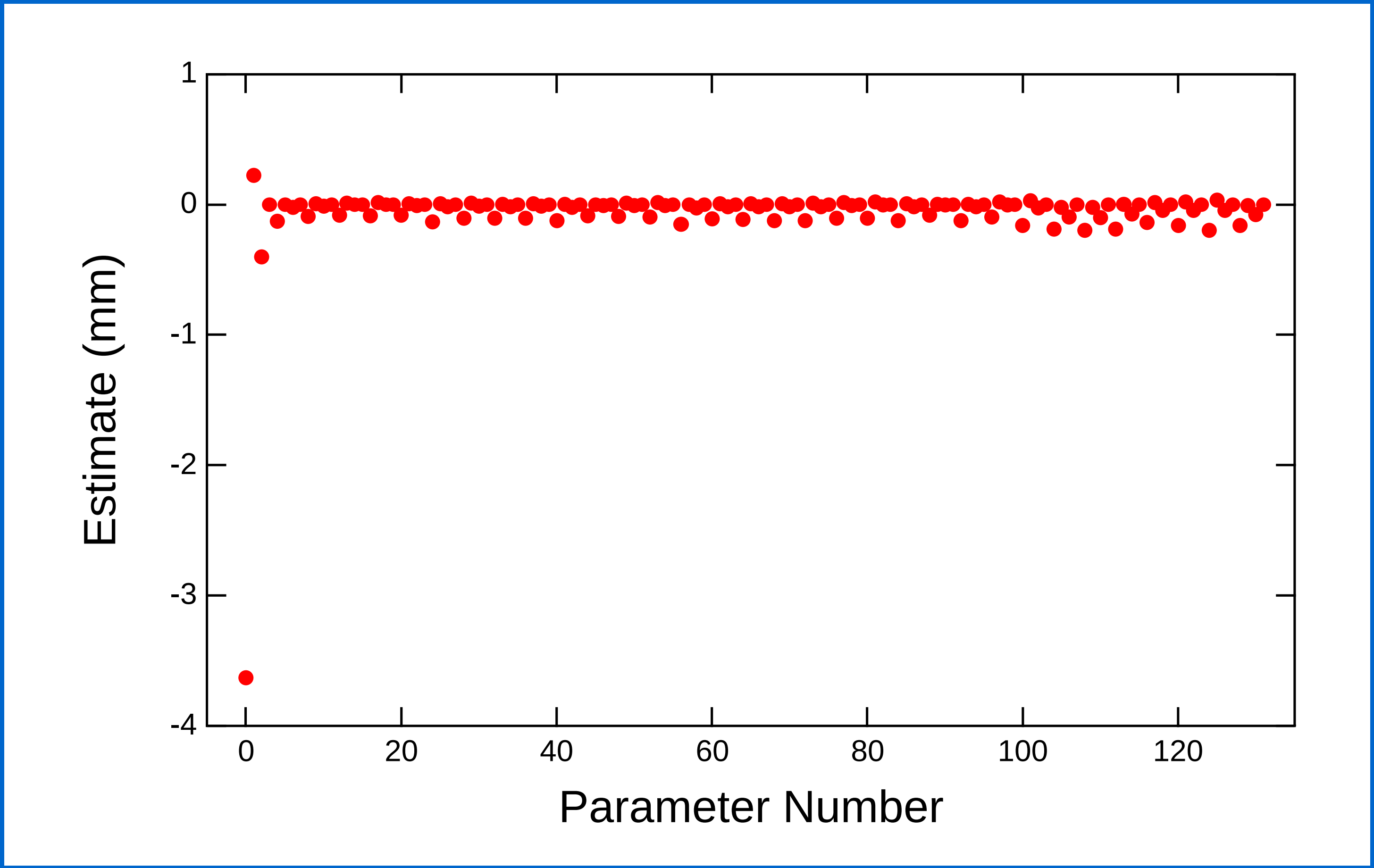
Form Double Differences



Simulated atmosphere results in zero mm for all double-difference phases but for the seven that involve Ray 0, which are 10 mm.

Perform Least Squares

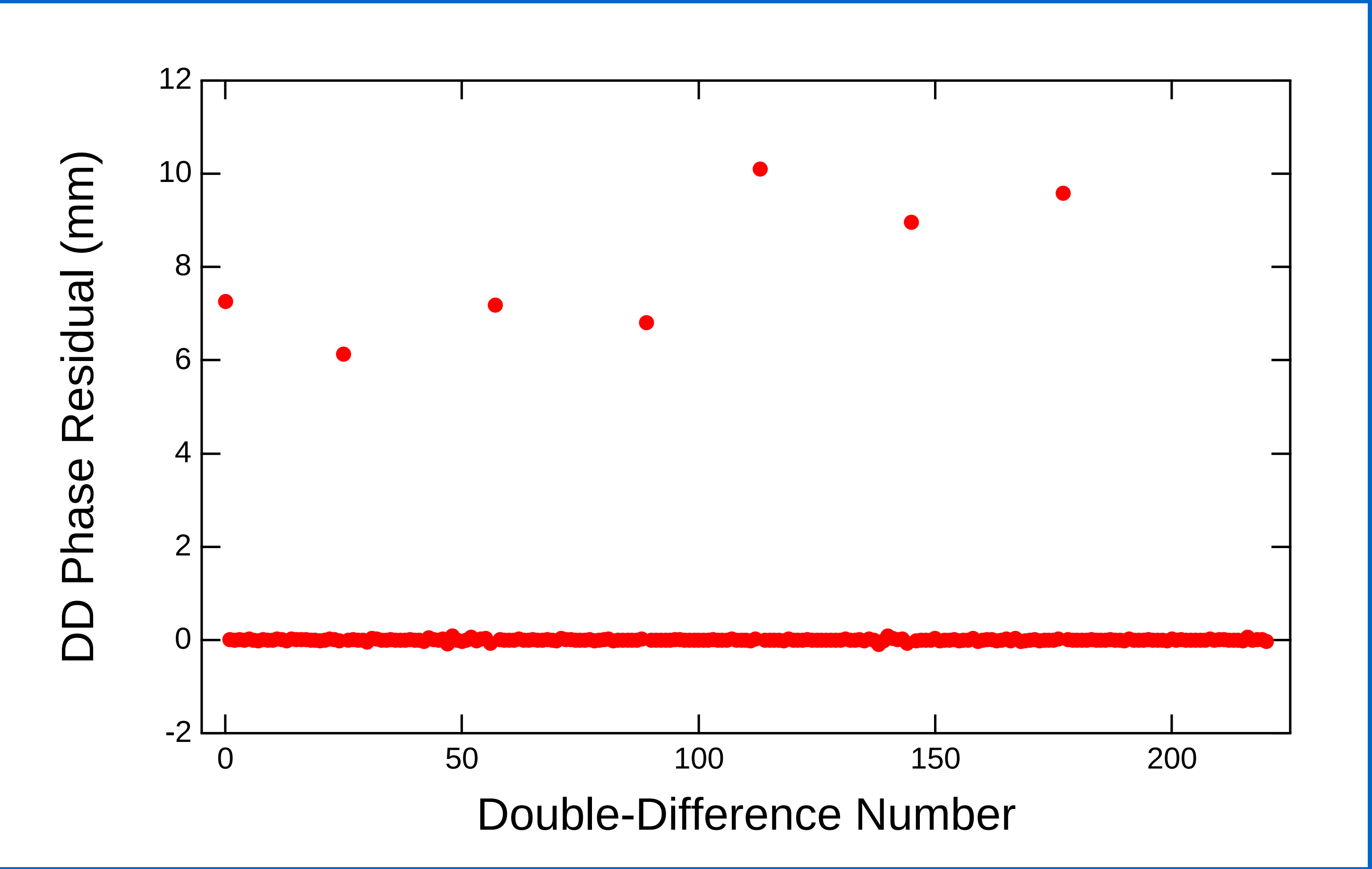
II



Least squares modeled the 10 mm anisotropy as an adjustment to all three atmospheric parameters of Site 1. The anisotropy is mainly absorbed by the zenith delay parameter (Parameter 0) probably because of the high elevation angle (55°) of Ray 0. The zenith delay parameter of the last eight sites also deviates from zero at the 0.2 mm level. These are the distant (east-coast) sites that help estimate absolute zenith delay values.

Calculate Double-Difference Residuals

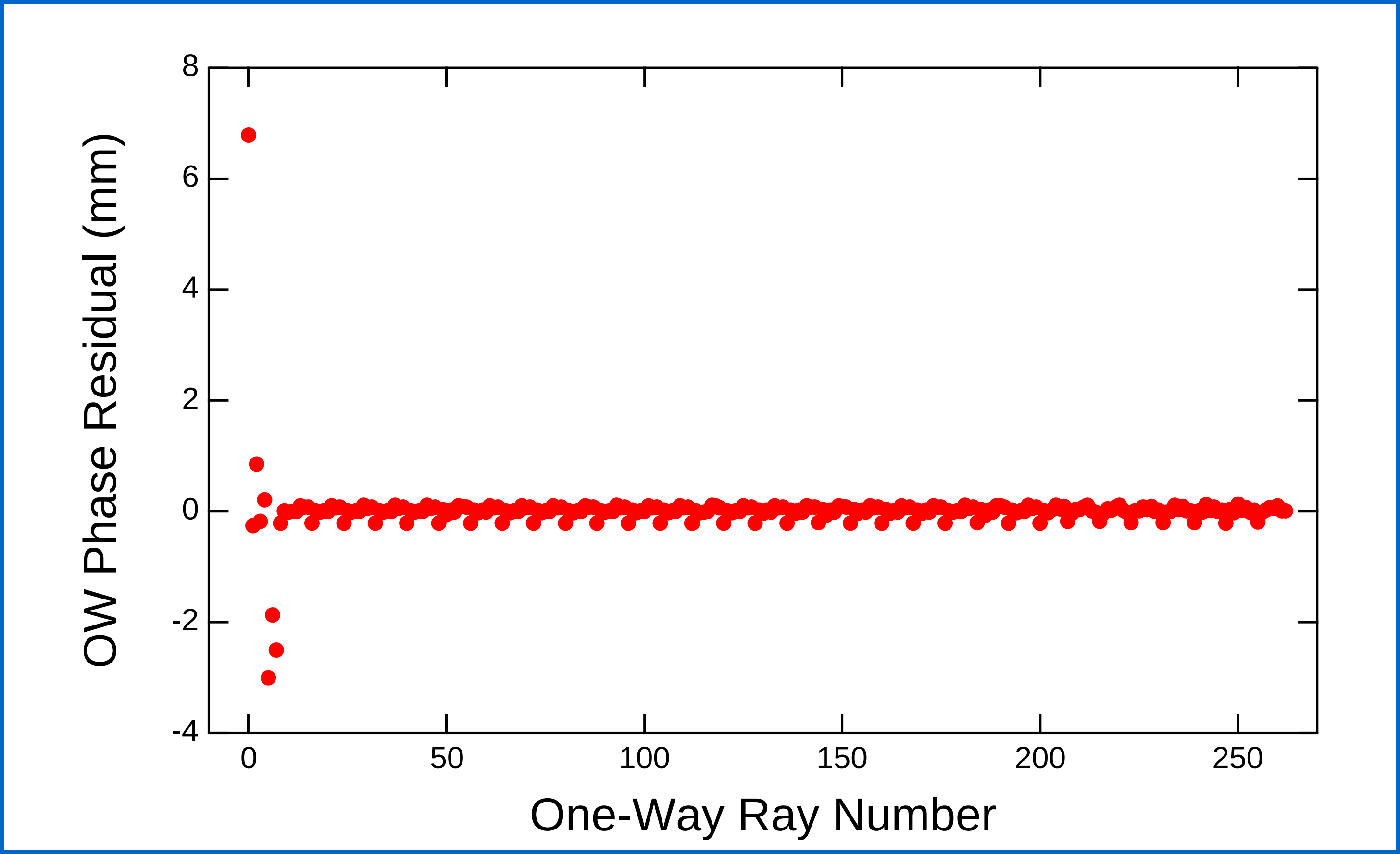
II



Atmosphere for the double-difference residuals involving Site 1 is not constant since the least-squares solution modeled the anisotropy as (mainly) a zenith-delay adjustment.

II

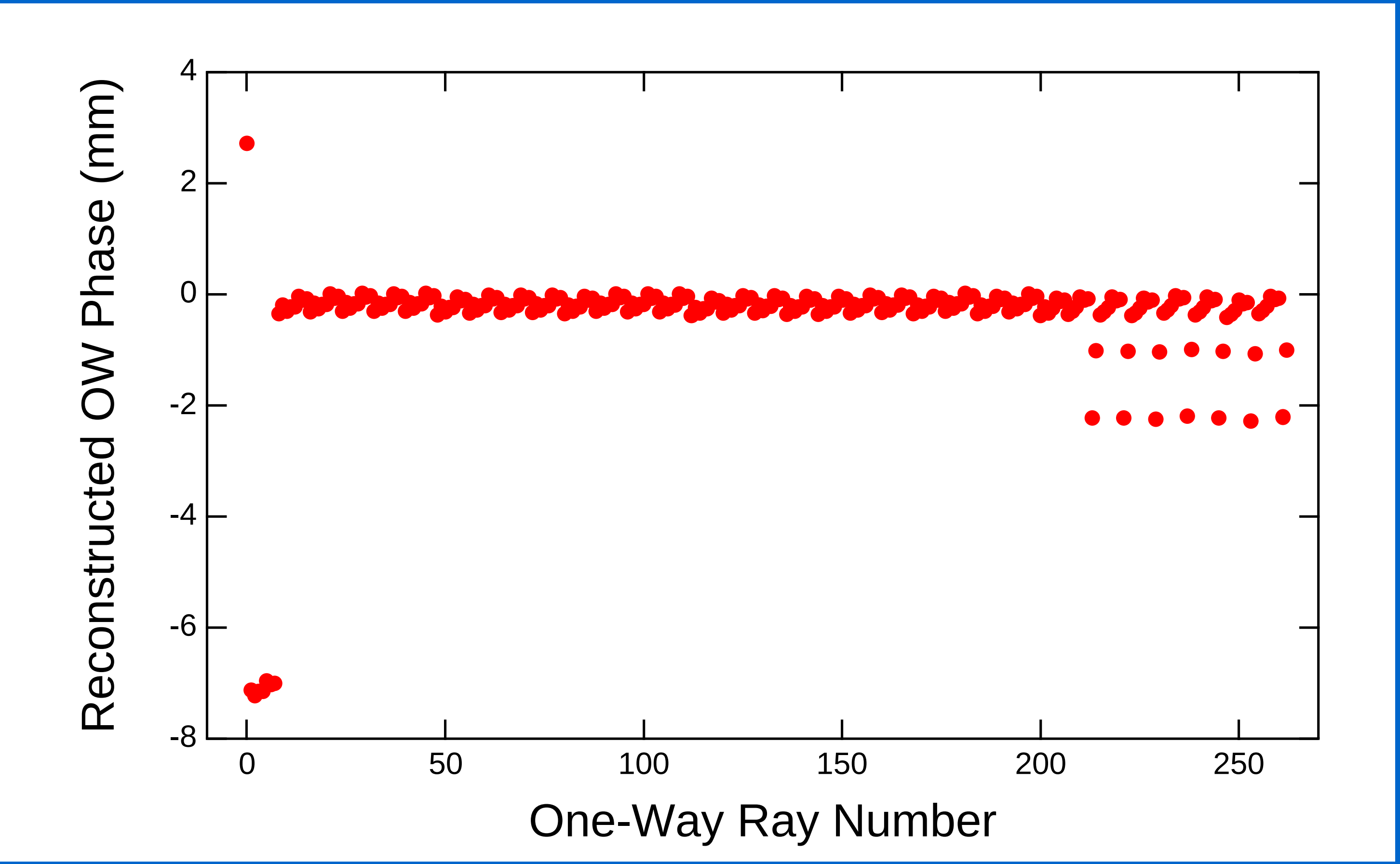
Unwrap Double-Difference Residuals



One-way phase residuals reflect the mapping of the anisotropy into the estimated model parameters.

Reconstruct Atmosphere

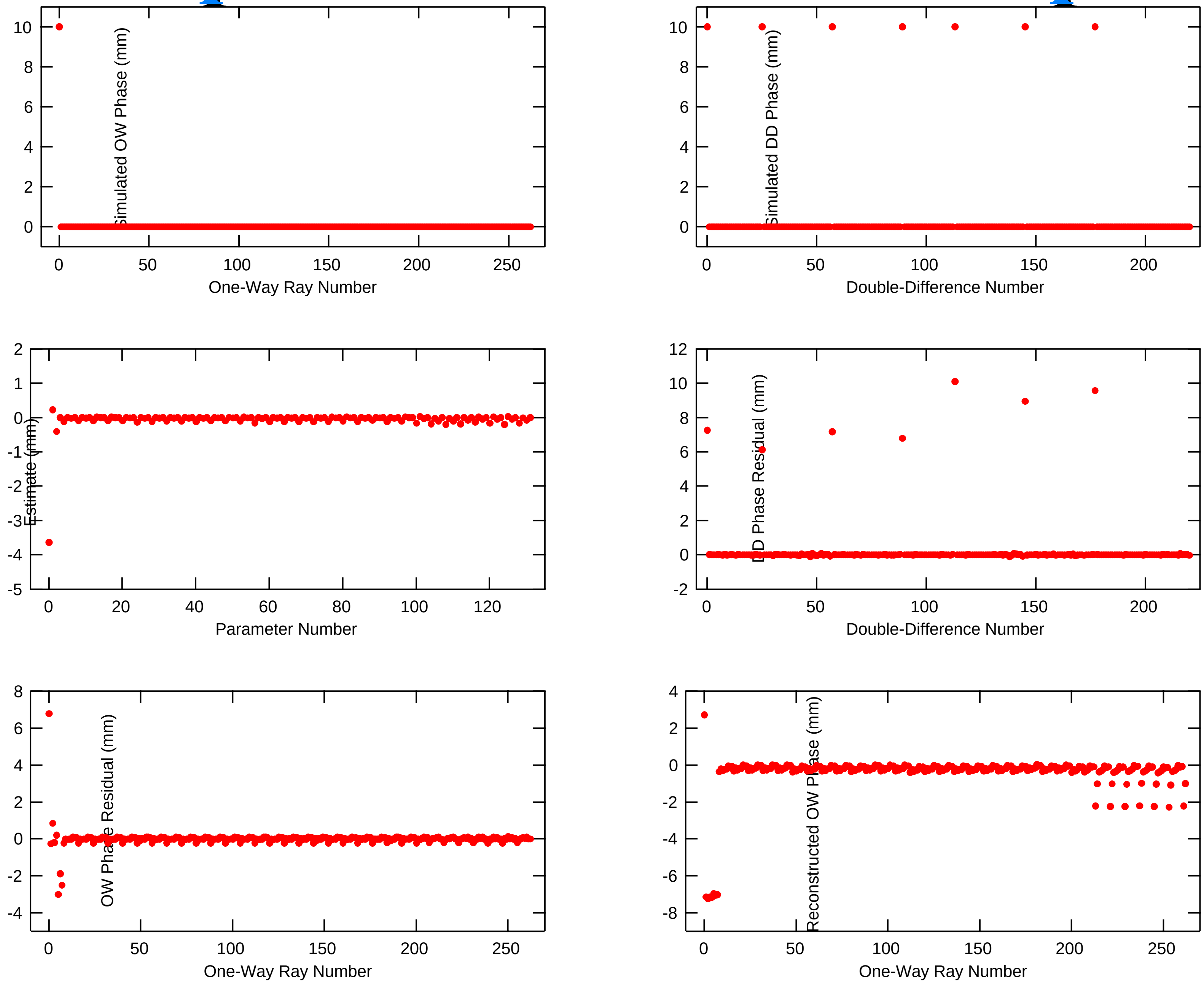
II



Site 1 recovers the 10 mm difference between Ray 0 and the rest of rays, but all its reconstructed phases are biased. The reconstructed phases of satellites that are observed by only the distant sites are also biased by ~1 and ~2 mm. These are low elevation-angle satellites (~15º and ~10°, respectively) rising from the east.

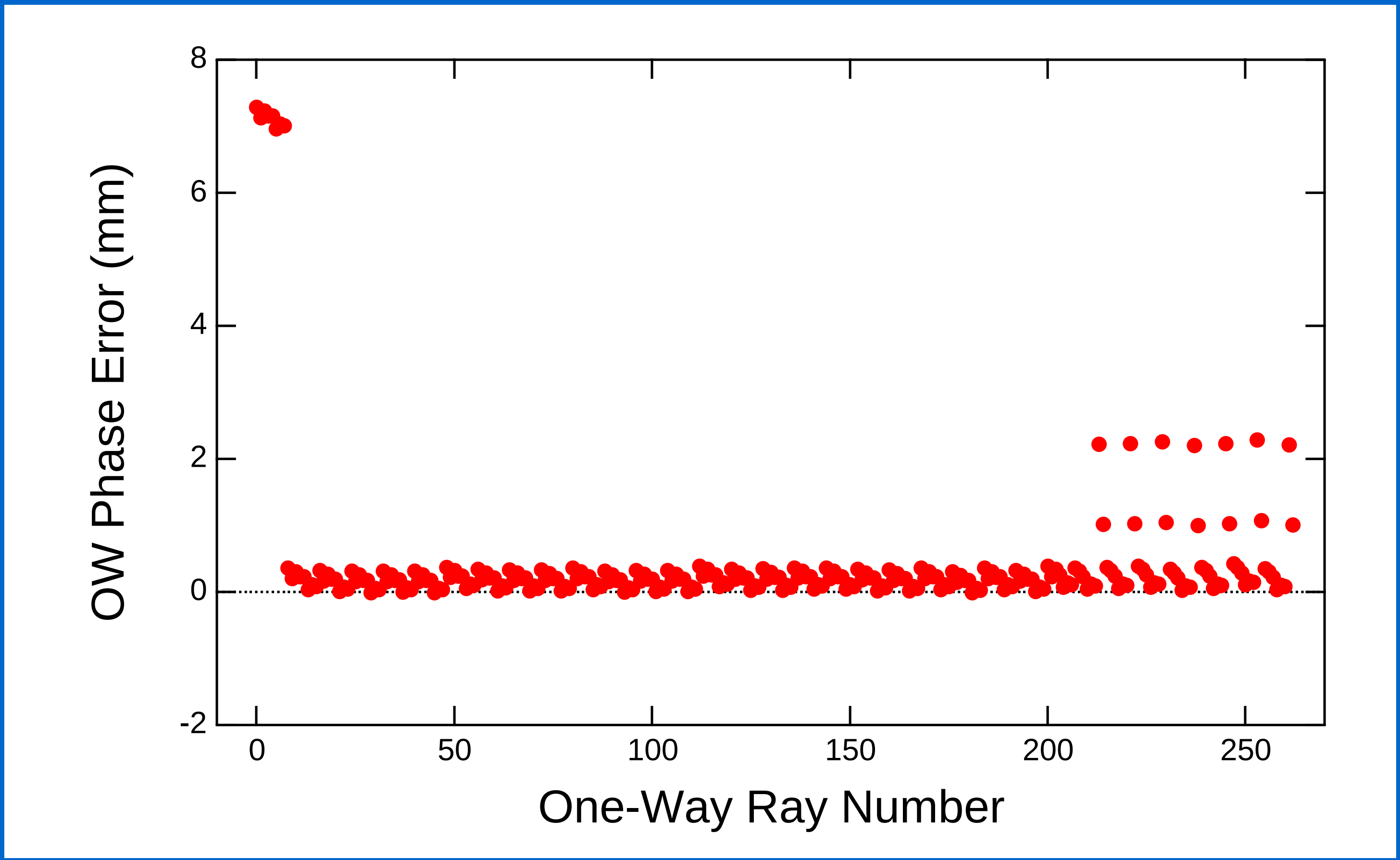
Composite of Previous Graphs

II



Compare Simulated and Reconstructed Atmospheres

II



All reconstructed one-way phases at the site that observed the 10 mm anisotropy are in error by ~7 mm relative to the simulated one-way phases. Largest error for other phases amounts to ~2 mm. The RMS of the reconstructed one-way phases is 1.3 mm.

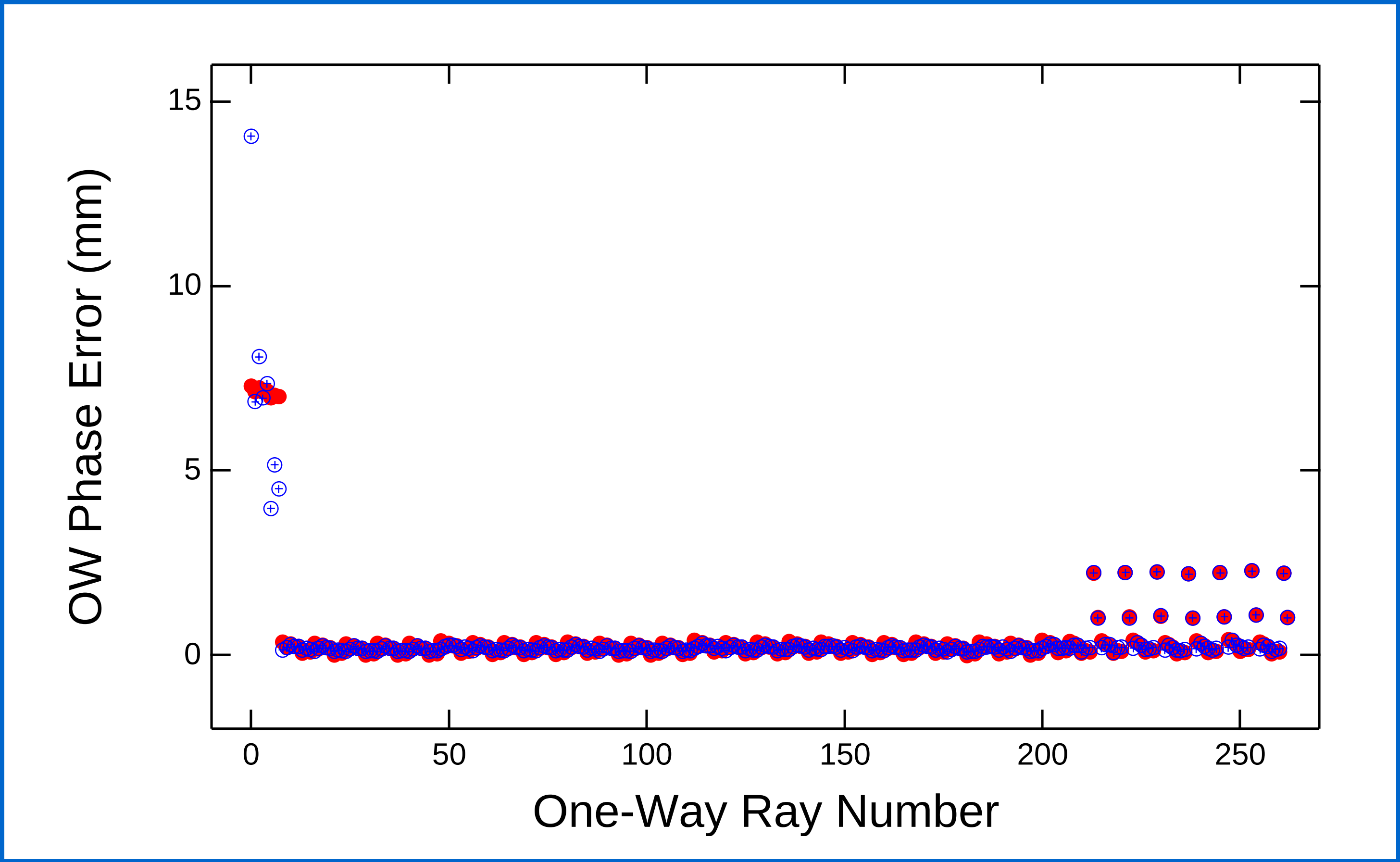
II

Statistical Assessment

- The standard method leads to significant systematic errors.
- Nevertheless, we expect that a statistical assessment will lead to the conclusion that there is some improvement over an approach that ignores anisotropies.
- To statistically assess the standard method, we reconstruct one-way phases without using the *Alber et al.* [2000] algorithm, i.e., without adding the unwrapped double-difference postfit residuals to the atmospheric parameter estimates, and compare the RMS errors of the reconstruction of both approaches.

RMS Comparison

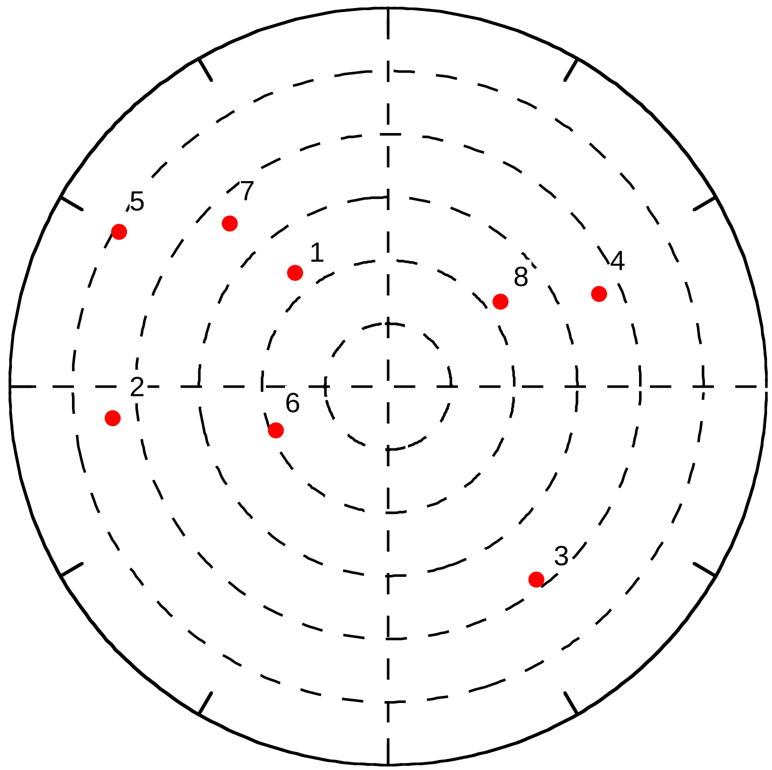
II



The RMS of the reconstruction error using the standard method (red) is 1.3 mm. The RMS when not using this method (blue) is 1.4 mm. The ~6% improvement comes from the site that observed the anisotropy. Although potentially formally significant depending on the number of data, the improvement is irrelevant since the standard method leads to errors in the reconstruction that are relatively much greater.

Extension of Simulation II

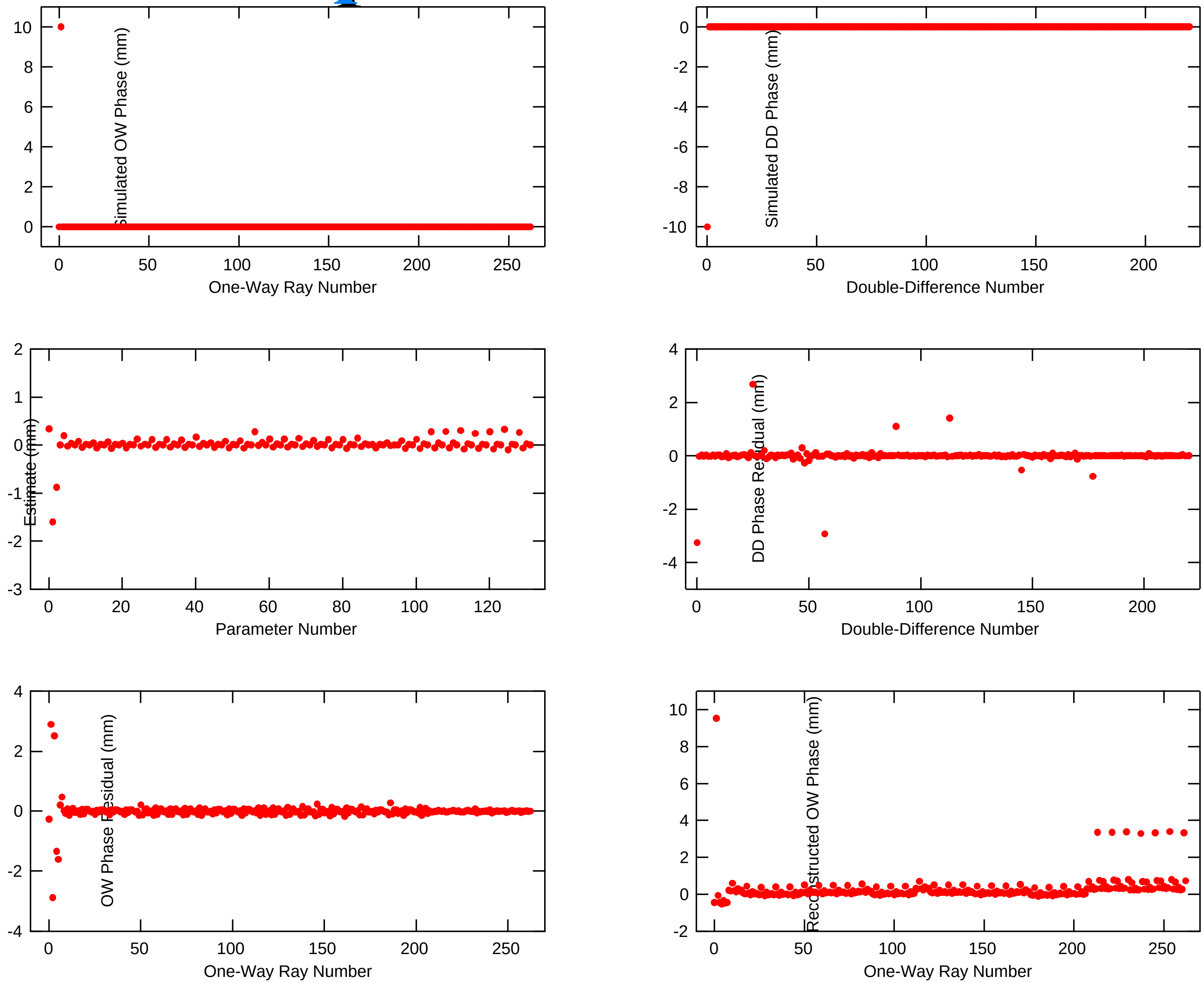
II



Sky plot at site ARM1. The satellite involved in the previous simulation (Satellite 1) is used as a “base satellite” in the algorithm that forms an independent set of double-differences from one-way observations. Other satellites do not form as many double-differences. To exhaustively explore the effect of satellite geometry on the reconstructed slant wet delays, in each of the following seven simulations the single anisotropy will be localized along the line-of-sight to a different satellite, shown as 2–8.

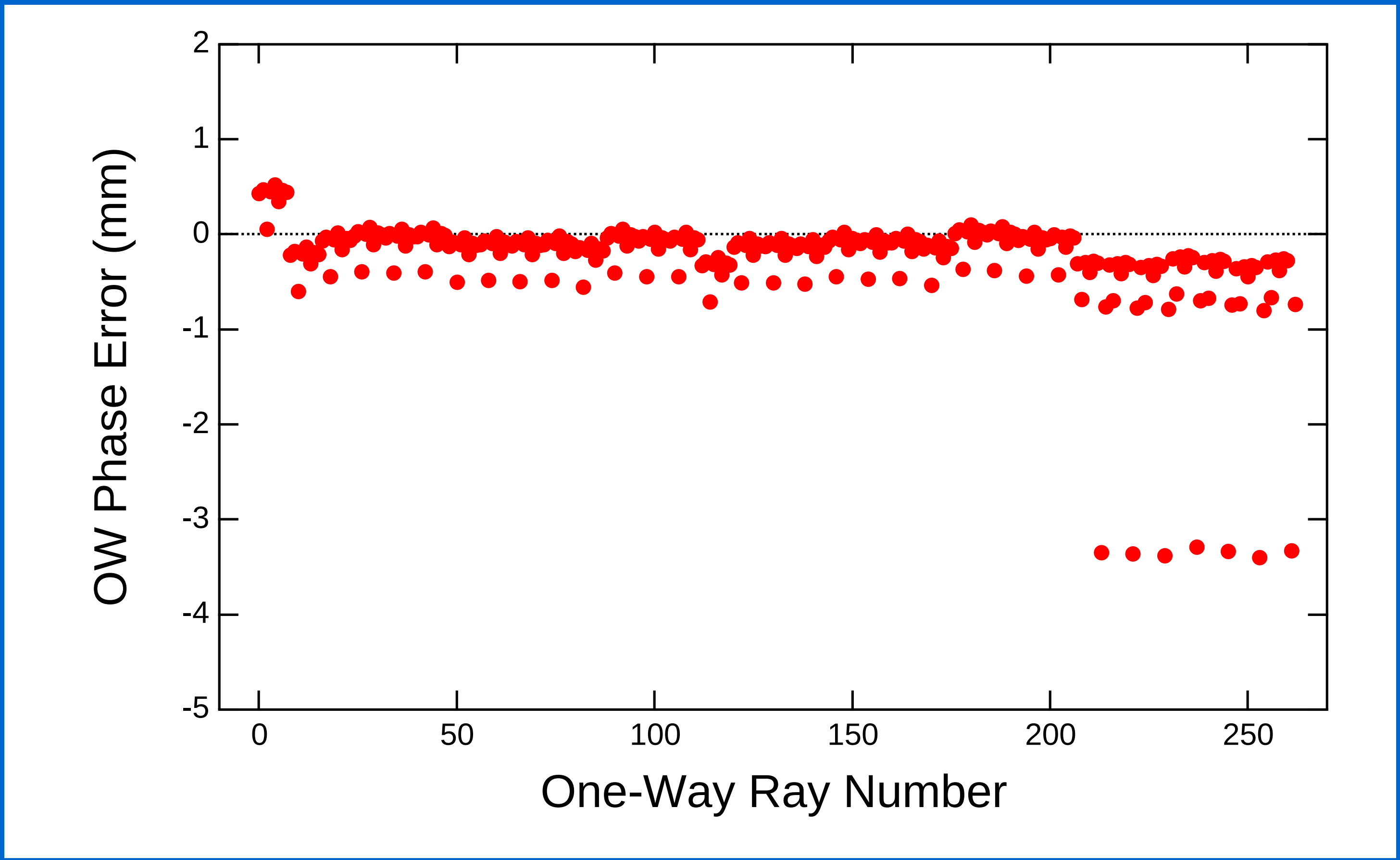
Composite of Satellite 2

II



Compare Simulated and Reconstructed Atmospheres

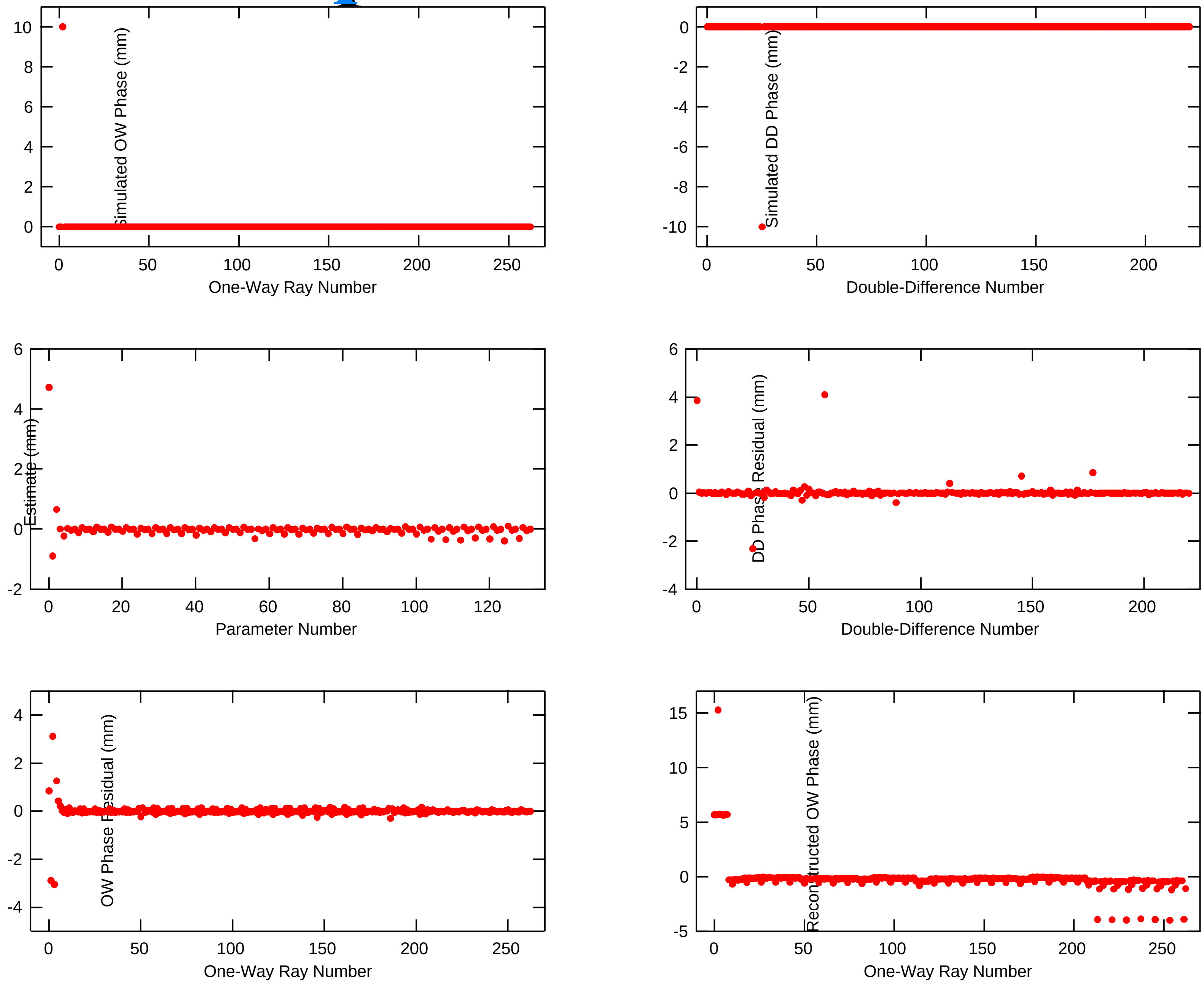
II



All reconstructed one-way phases at ARM1 are in error by ~0.5 mm. Other sites are in error at the same level, with largest value of ~3 mm. The RMS is 0.6 mm, 0.7 mm when not using the standard method, or a 13% improvement.

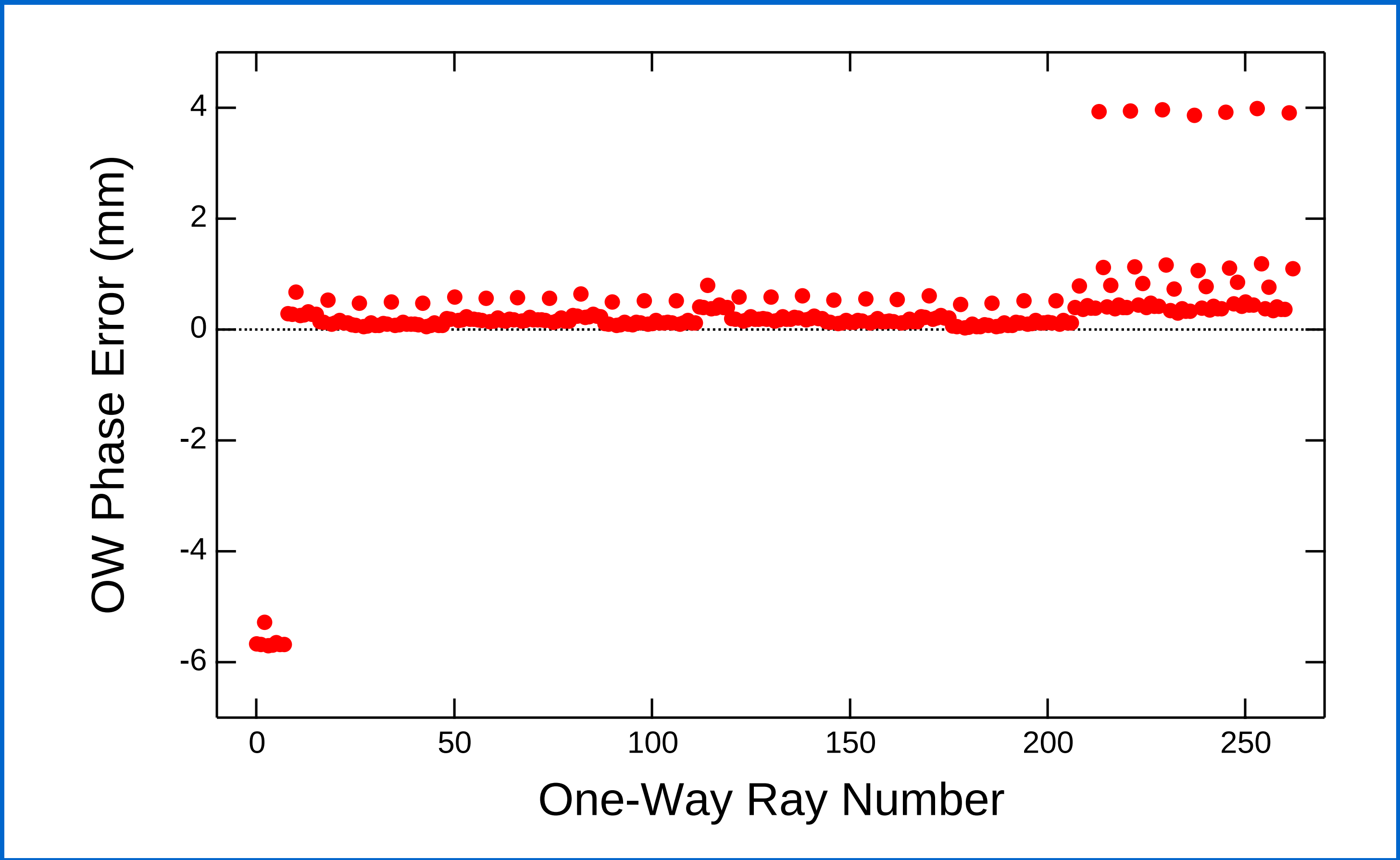
Composite of Satellite 3

II



Compare Simulated and Reconstructed Atmospheres

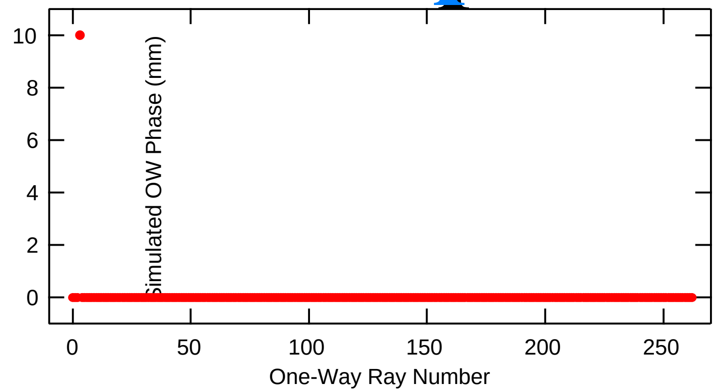
II

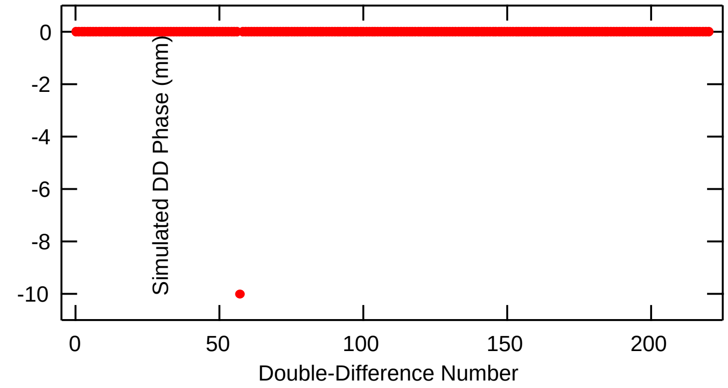


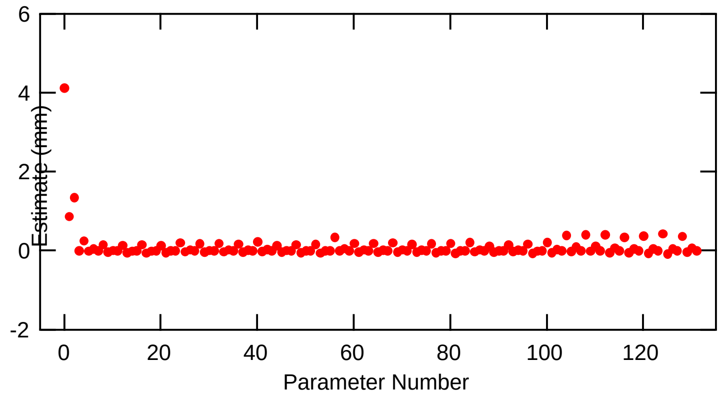
All reconstructed one-way phases at ARM1 are in error by ~6 mm. Other sites are in error by ~1 mm, with largest value of ~4 mm. The RMS is 1.2 mm, 1.3 mm when not using the standard method, or a 4% improvement.

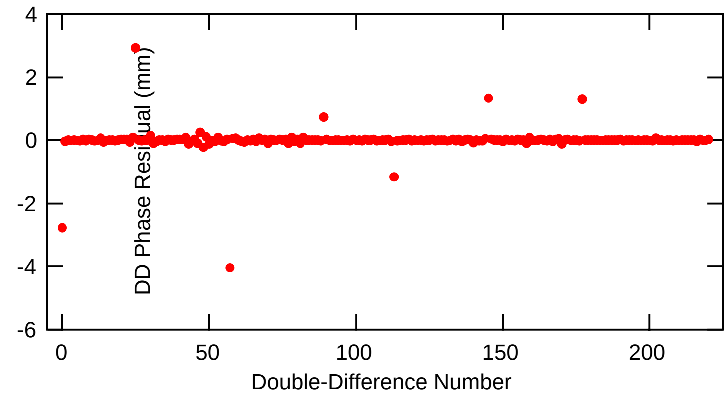
Composite of Satellite 4

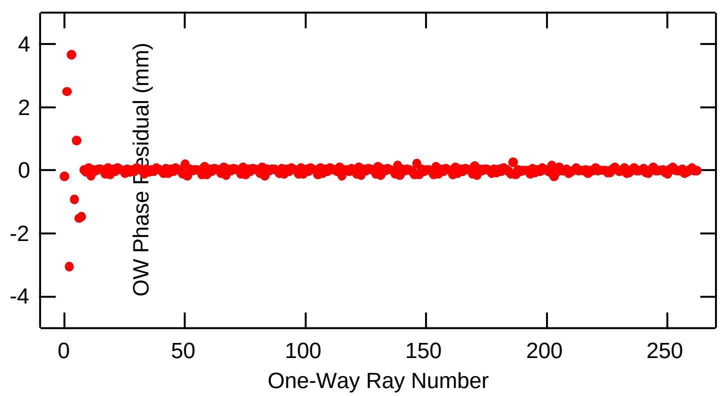
II

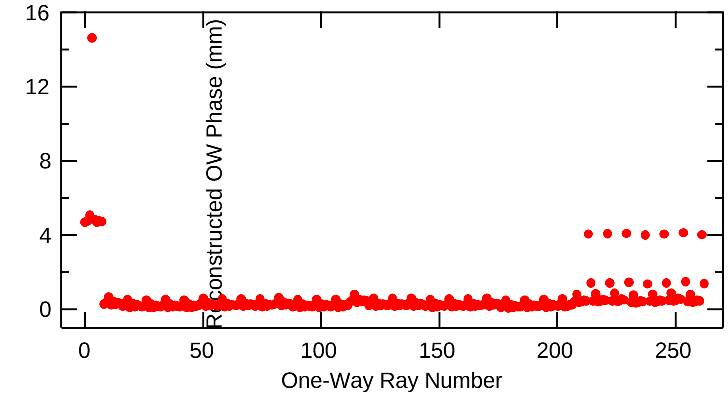






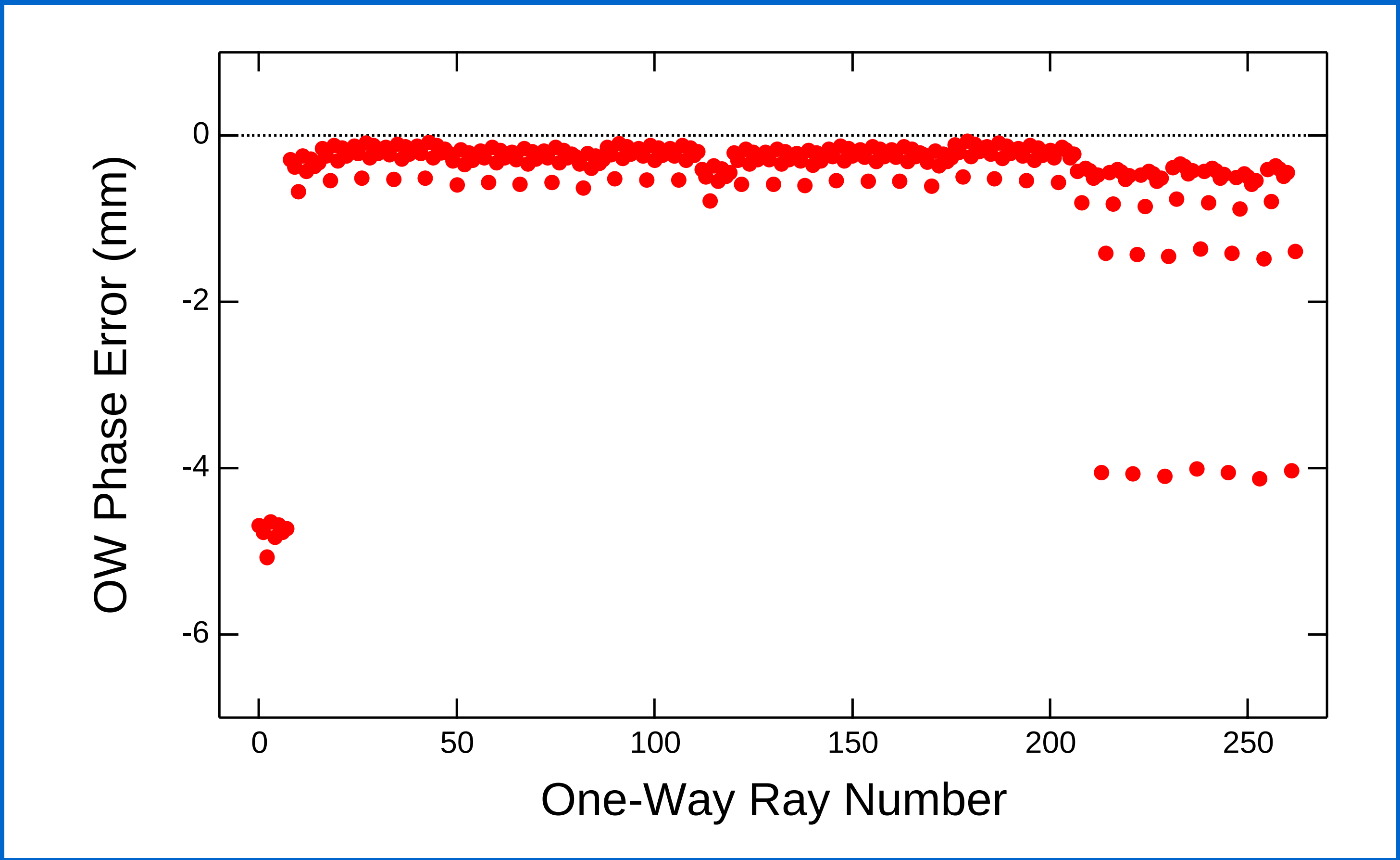






Compare Simulated and Reconstructed Atmospheres

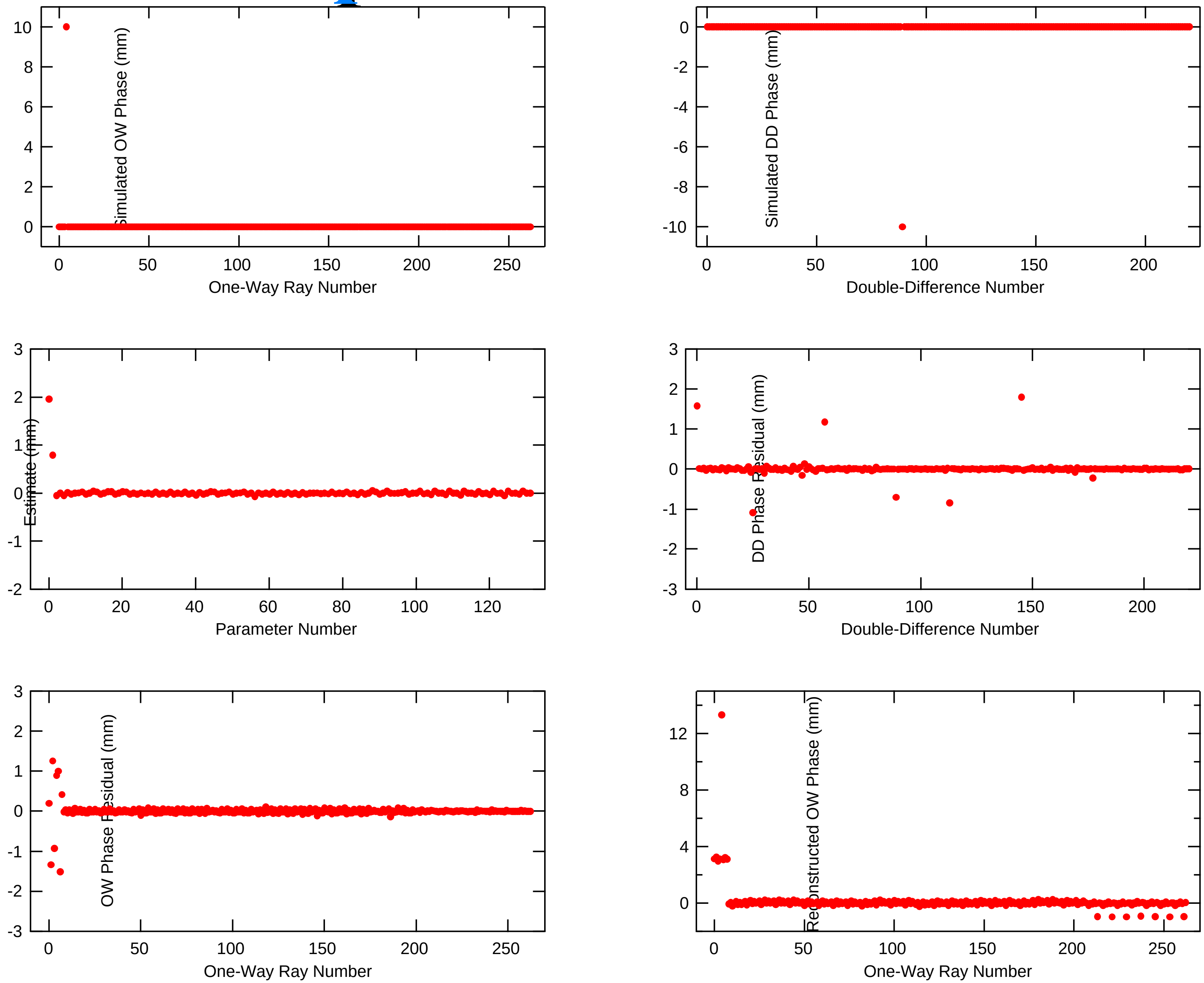
II



All reconstructed one-way phases at ARM1 are in error by ~5 mm. Other sites are in error by ~1 mm, with largest value of ~4 mm. The RMS is 1.1(4) mm, 1.2 mm when not using the standard method, or a 5% improvement.

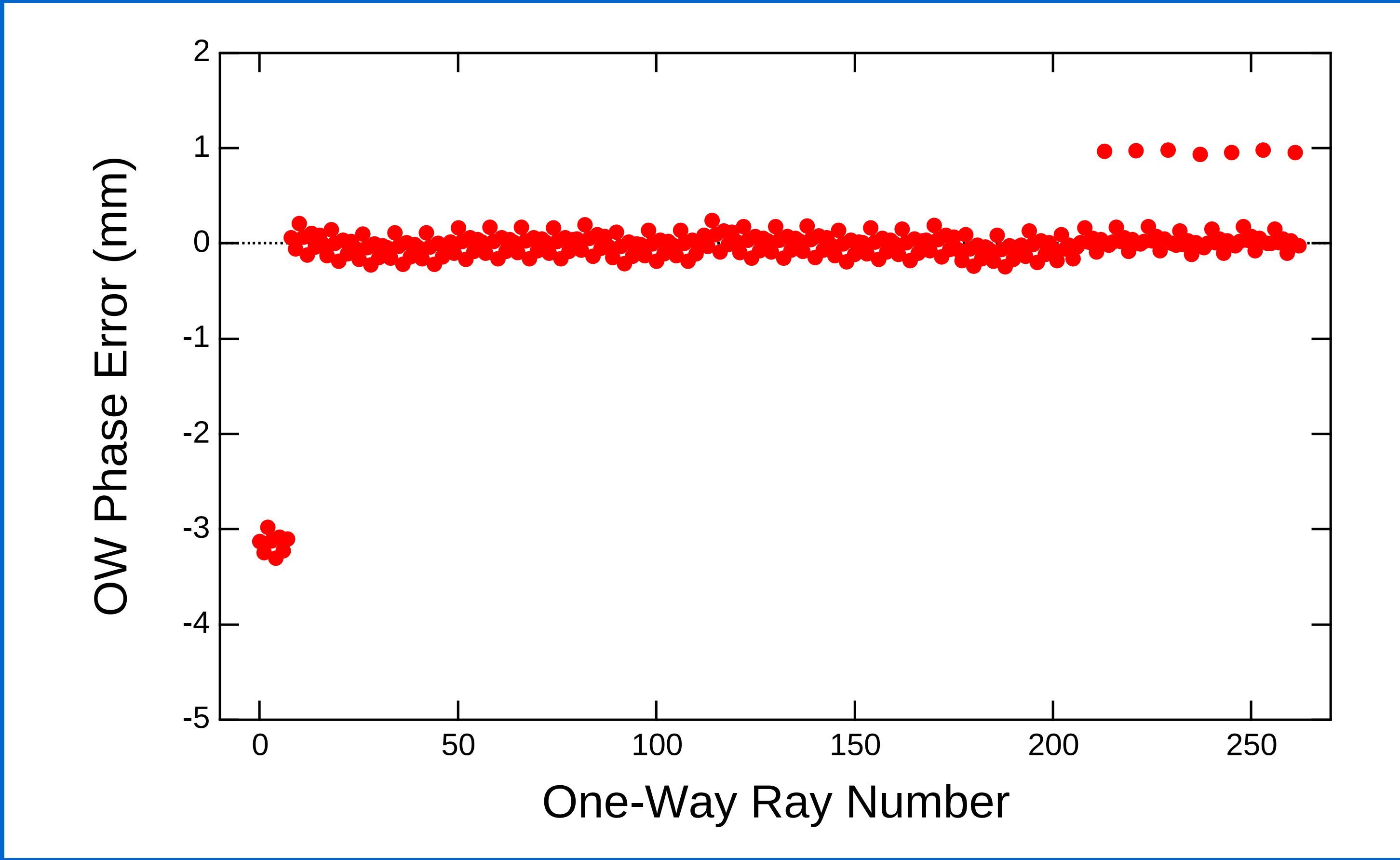
Composite of Satellite 5

II



Compare Simulated and Reconstructed Atmospheres

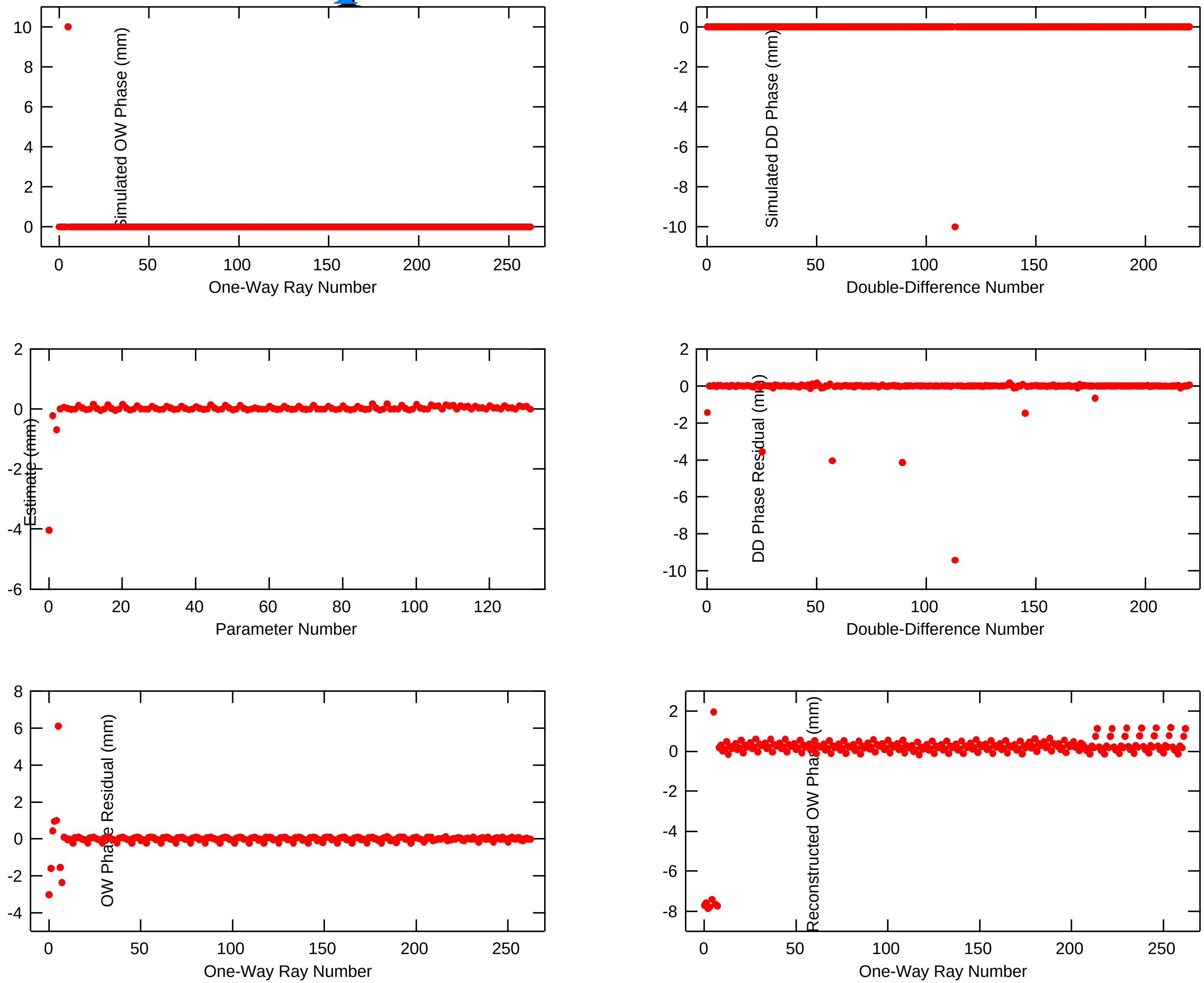
II



All reconstructed one-way phases at ARM1 are in error by ~3 mm. Largest error at other sites is ~1 mm. The RMS error is 0.5(8) mm, 0.6(1) mm when not using the standard method, or a 5% improvement.

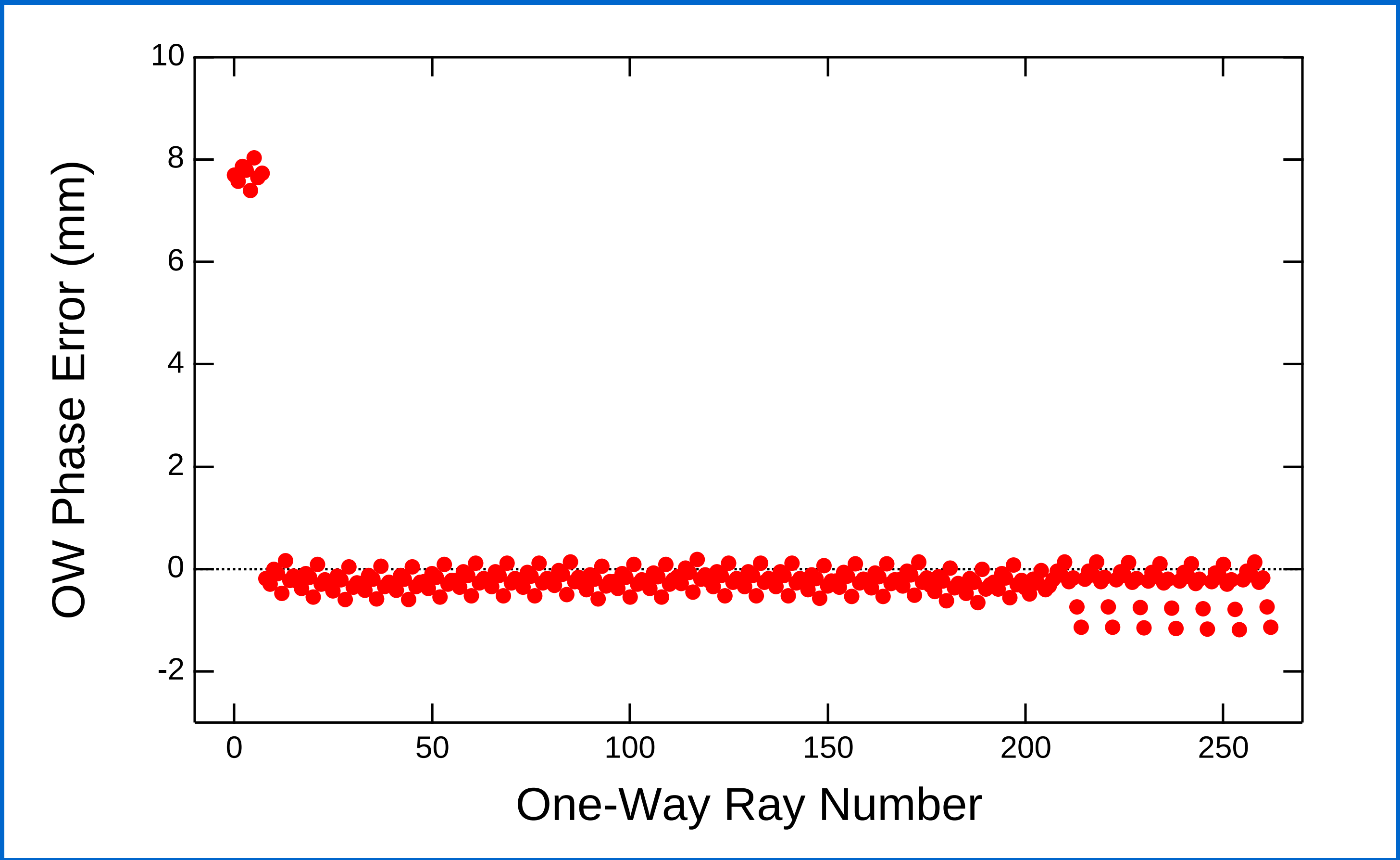
Composite of Satellite 6

II



Compare Simulated and Reconstructed Atmospheres

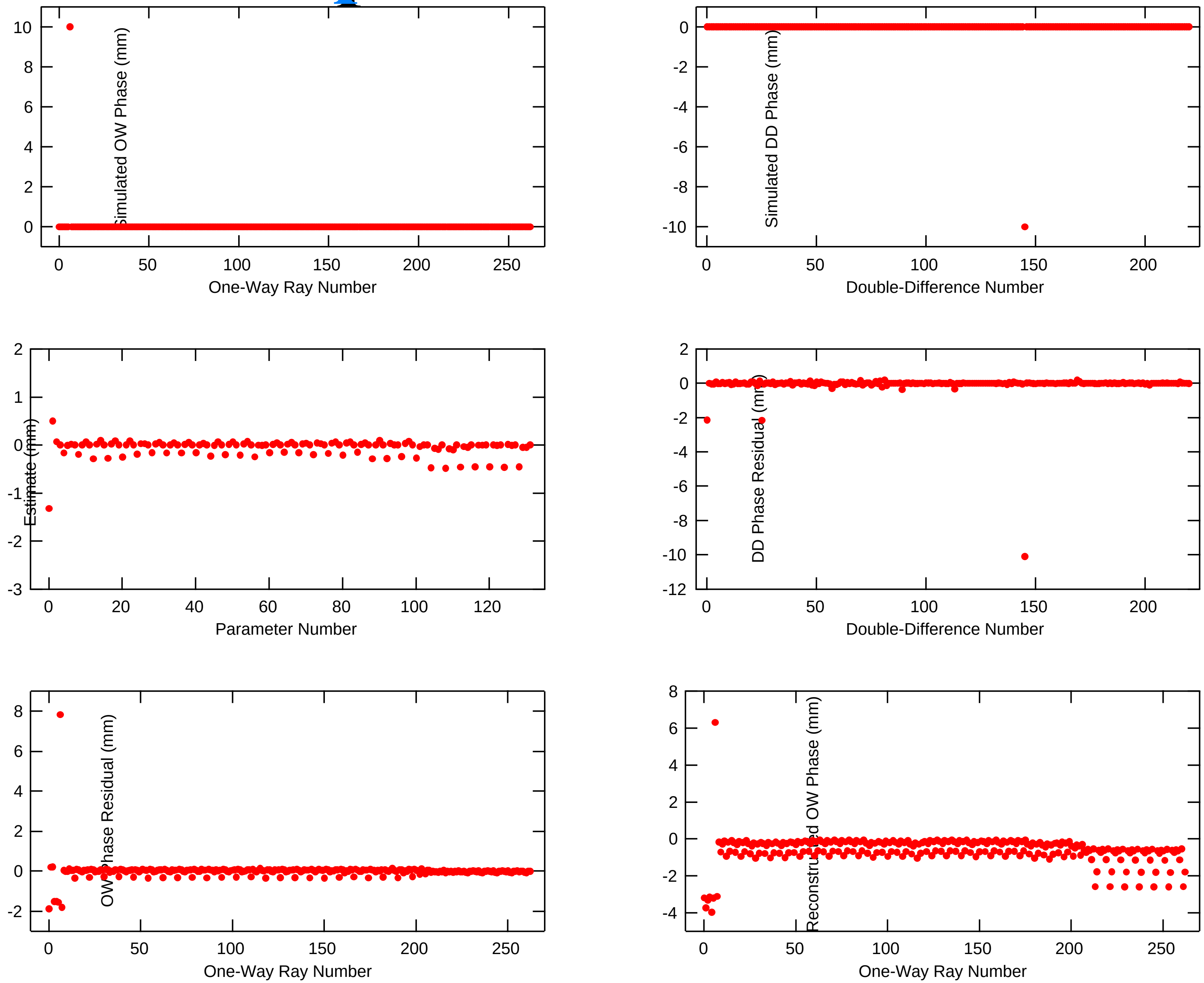
II



All reconstructed one-way phases at ARM1 are in error by ~8 mm. The RMS error is 1.5 mm, 1.4 mm when not using the standard method, or a 5% improvement.

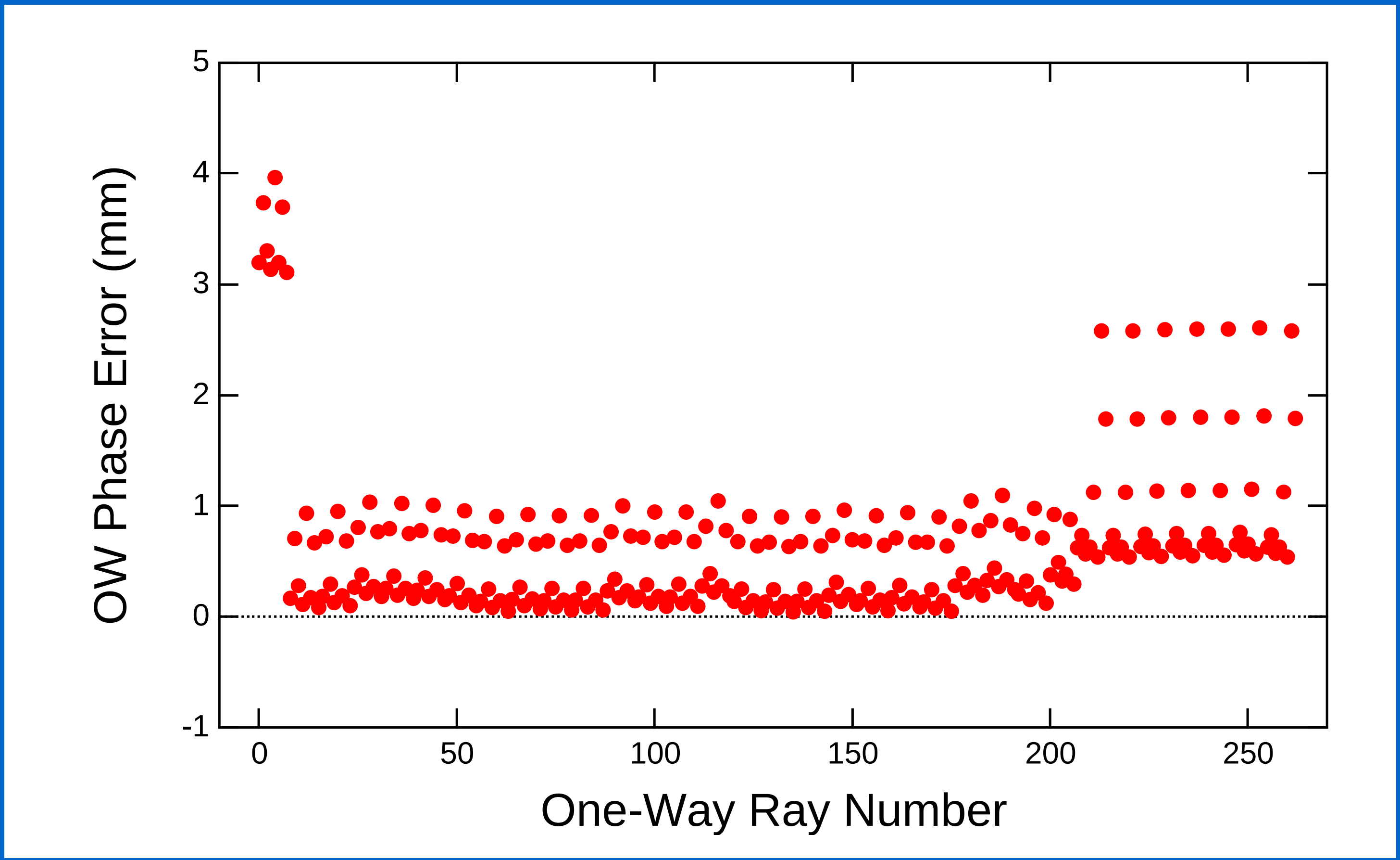
Composite of Satellite 7

II



Compare Simulated and Reconstructed Atmospheres

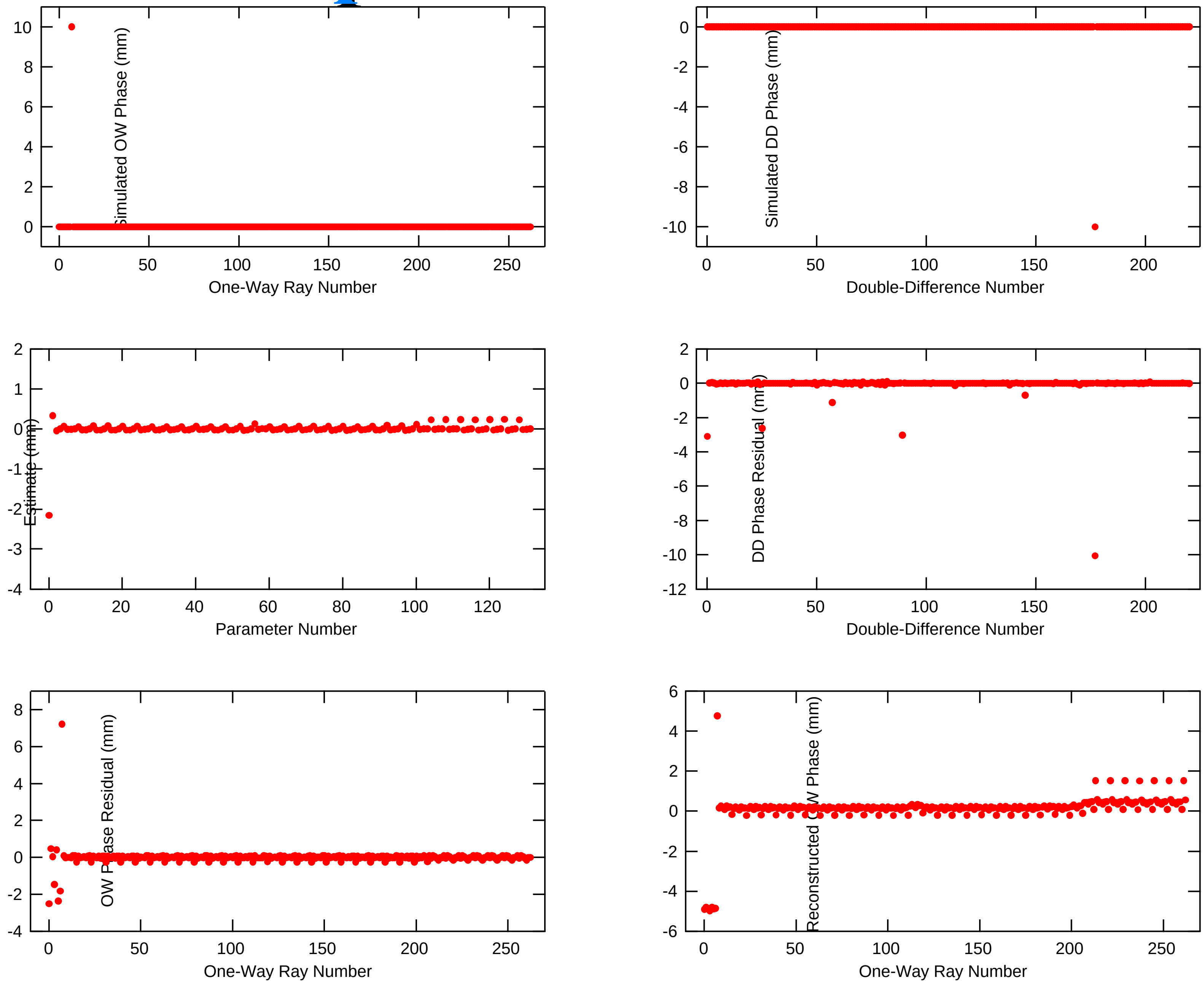
II



All reconstructed one-way phases at ARM1 are in error by ~3–4 mm. Other sites are in error at the ~1–3 mm level. The RMS is 1.0 mm, 1.1 mm when not using the standard method, or a 13% improvement.

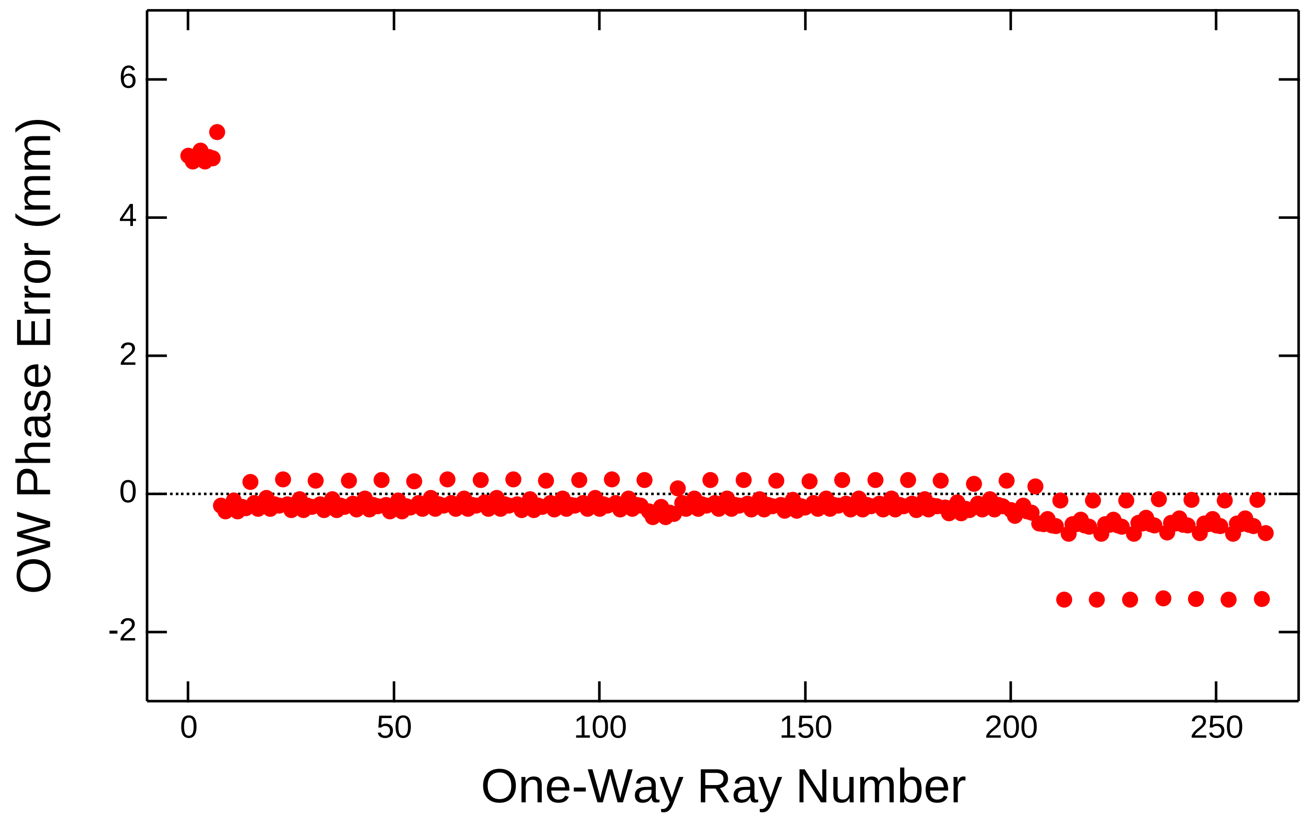
Composite of Satellite 8

II



Compare Simulated and Reconstructed Atmospheres

II



All reconstructed one-way phases at ARM1 are in error by ~5 mm. Largest error at the other sites is ~2 mm. The RMS is 0.9 mm, 1.1 mm when not using the standard method, or a 12% improvement

II

Summary of Simulation II

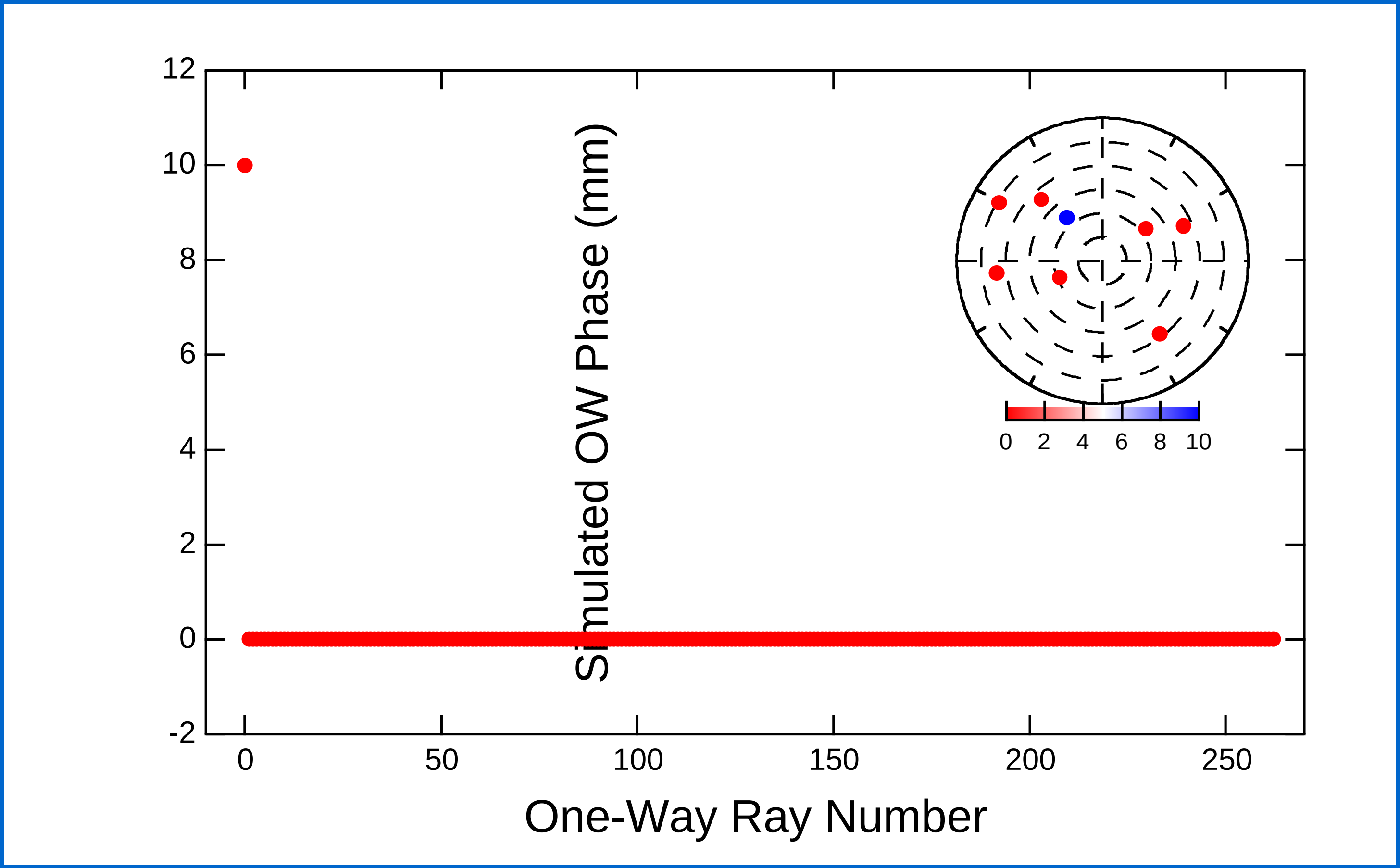
- All reconstructed one-way phases are biased.
- Errors amount up to 8 mm of phase for all one-way observations at the site that observed the single 10 mm anisotropy.
- Errors amount up to 4 mm at the sites that did not observed the anisotropy.
- The magnitude of the errors are commensurate with the size of the anisotropy signal that we are trying to measure.
- The standard method leads to improvements in the RMS error of reconstructed one-way phases of up to ~13%. This RMS improvement comes from the reconstructed phases at the site that observed the anisotropy.
- The RMS improvement is not a valid indicator of algorithm performance since the standard method leads to significant errors in the reconstruction.

Simulation III

Simulated atmosphere is perfectly homogenous but for an anisotropy along a single slant path. The atmospheric parameters are tightly constrained to their true value.

Simulate Atmosphere

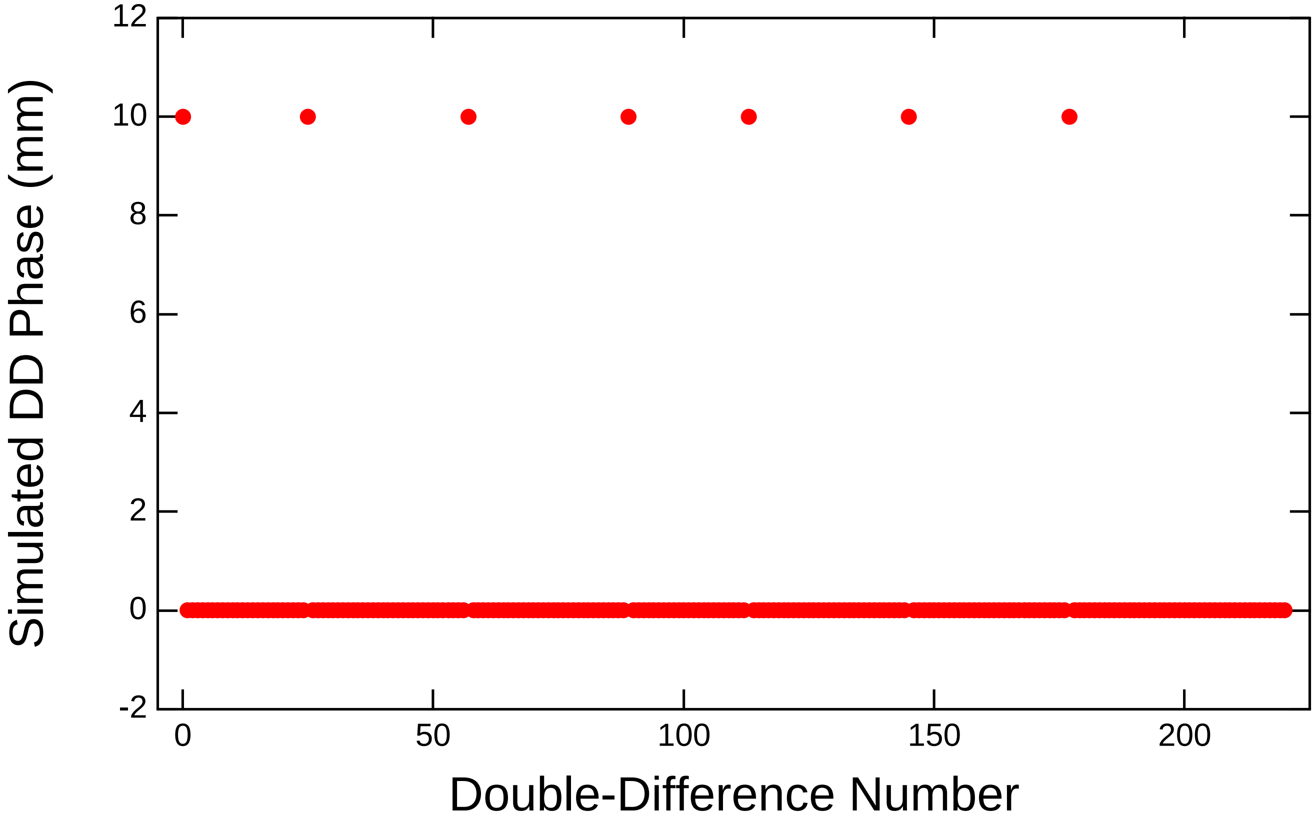
III



Simulated atmosphere is zero mm for all one-way phases but for Ray 0, which involves satellite 1 and site ARM1. The anisotropy amounts to 10 mm of one-way phase.

Form Double Differences

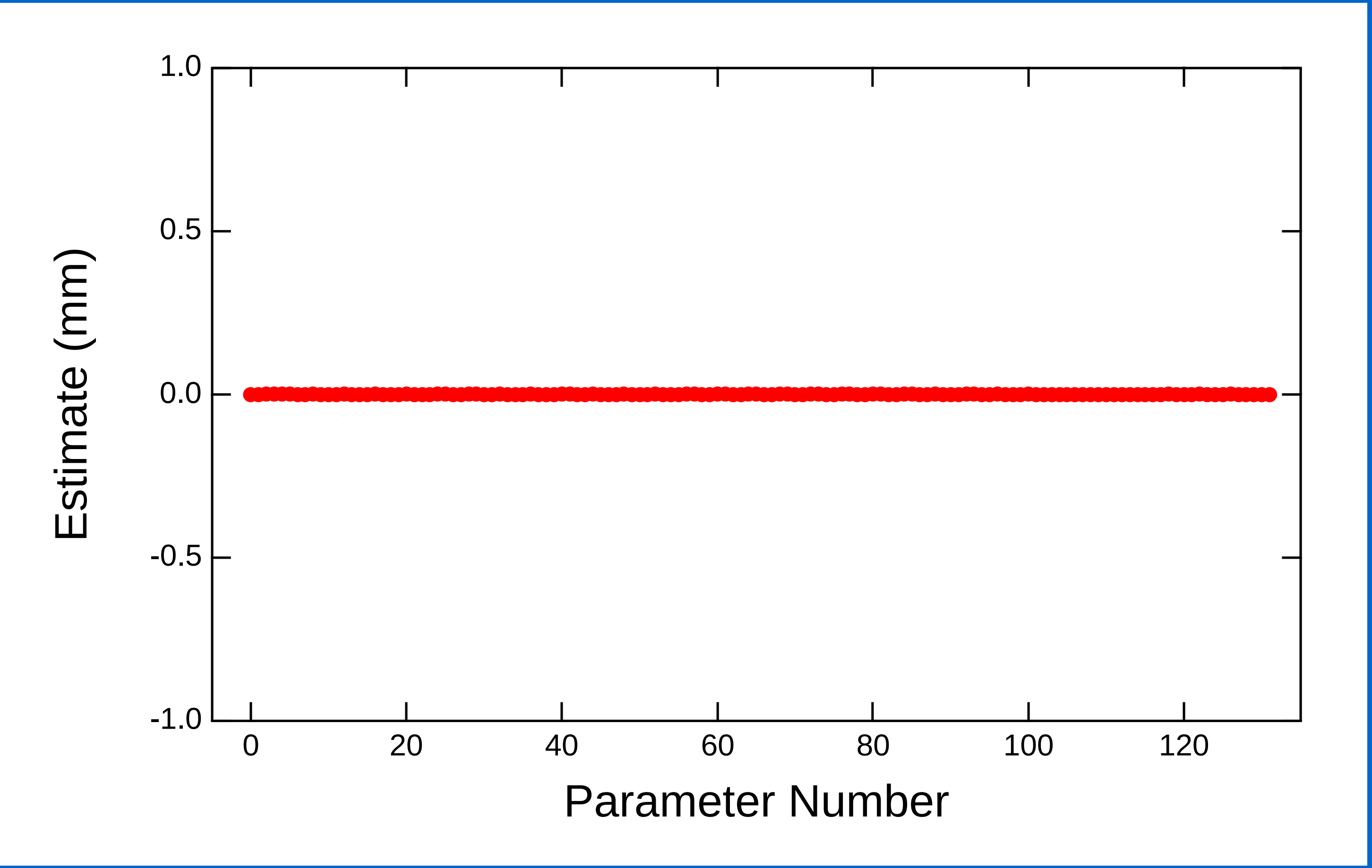
III



Simulated atmosphere results in zero mm for all double-difference phases but for the seven that involve Ray 0, which are 10 mm.

Perform Least Squares

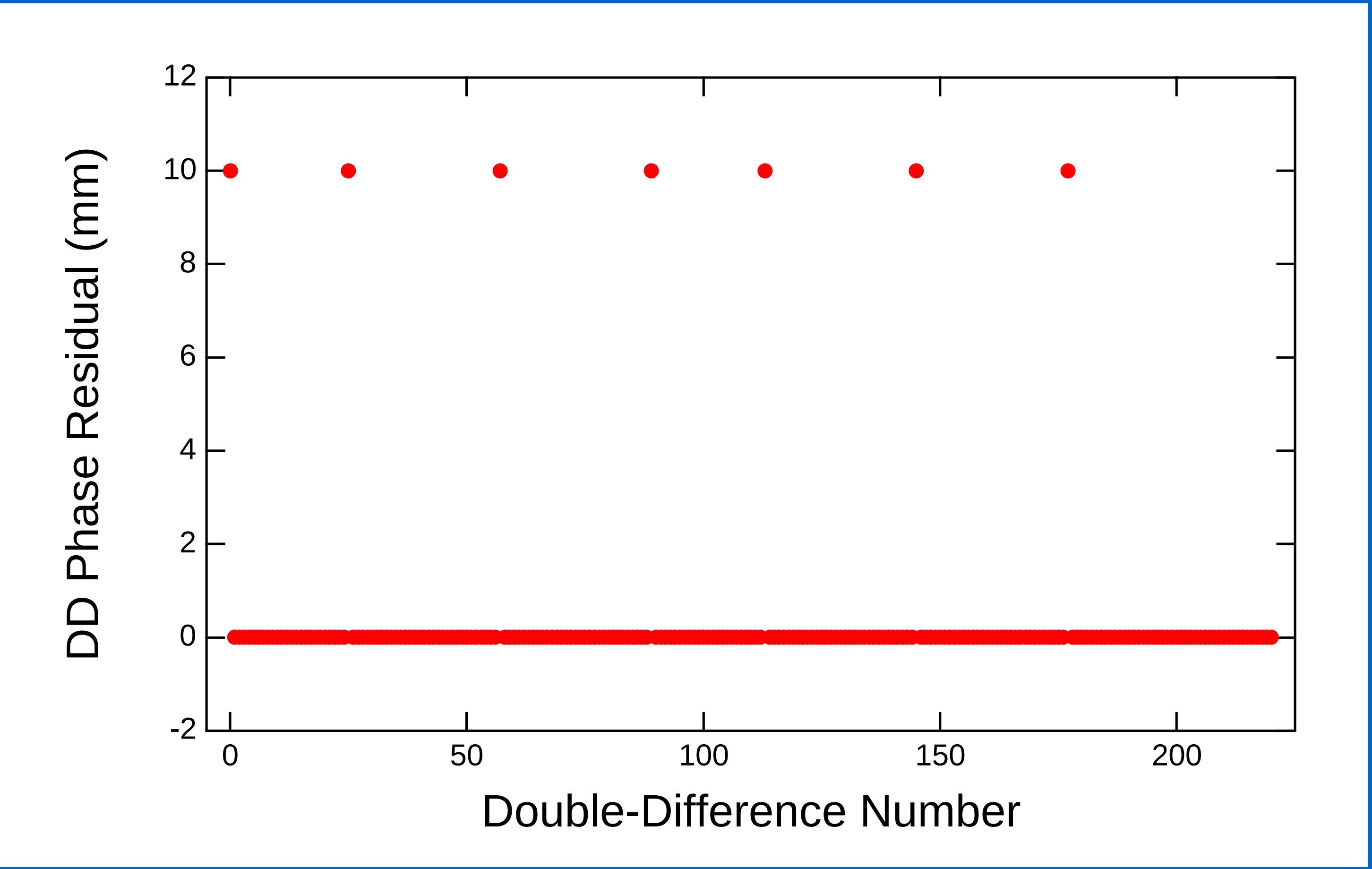
III



Estimate four parameters per site: zenith delay, north and east gradient, and vertical component of site position. All four parameters at all 33 sites are constrained to zero mm with an uncertainty of 0.001 mm.

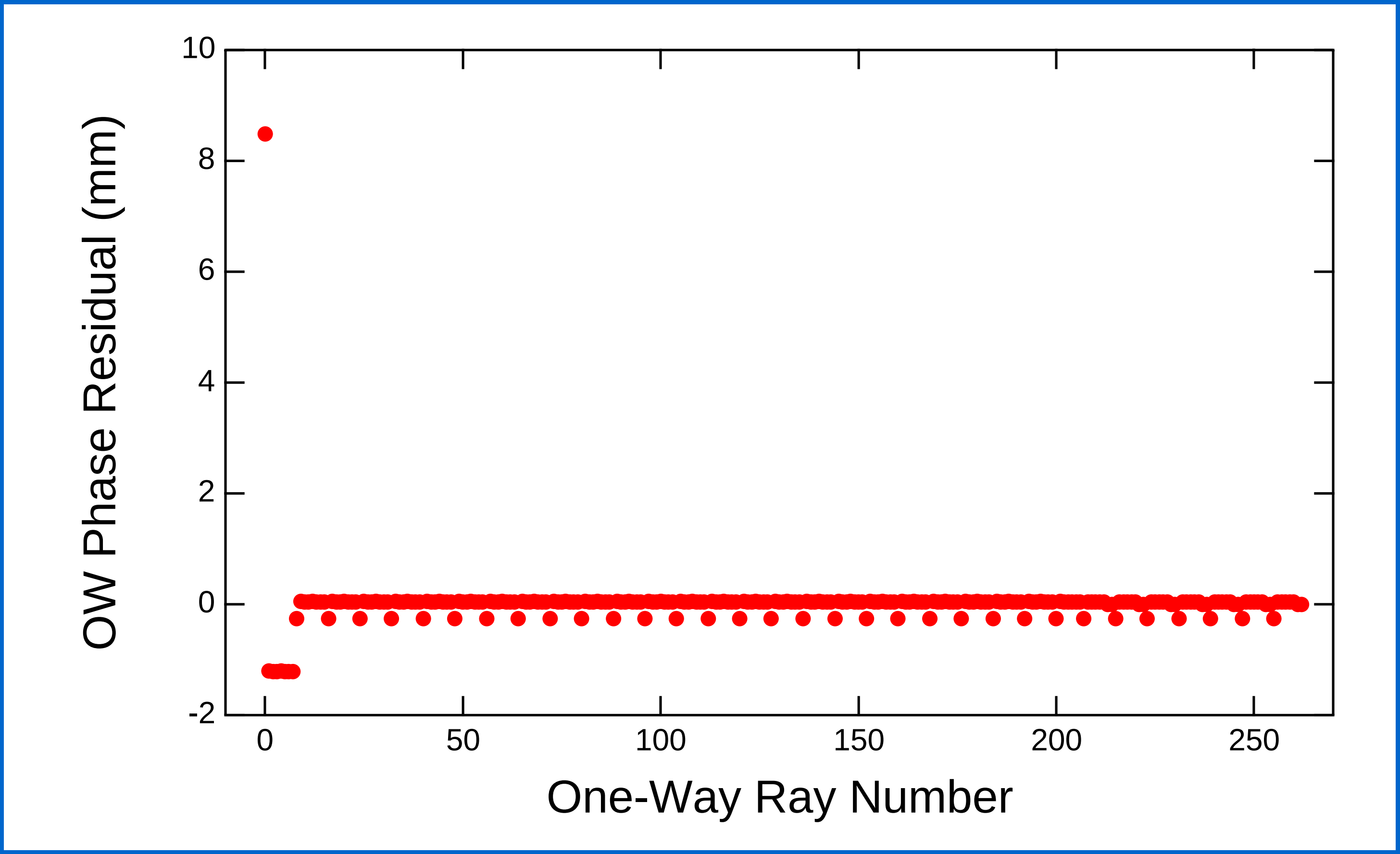
Calculate Double-Difference Residuals

III



Atmosphere for the double-difference residuals involving Ray 0 is constant (at the 0.001 mm level) since all parameter adjusts in the tightly constrained least-squares solution are zero mm.

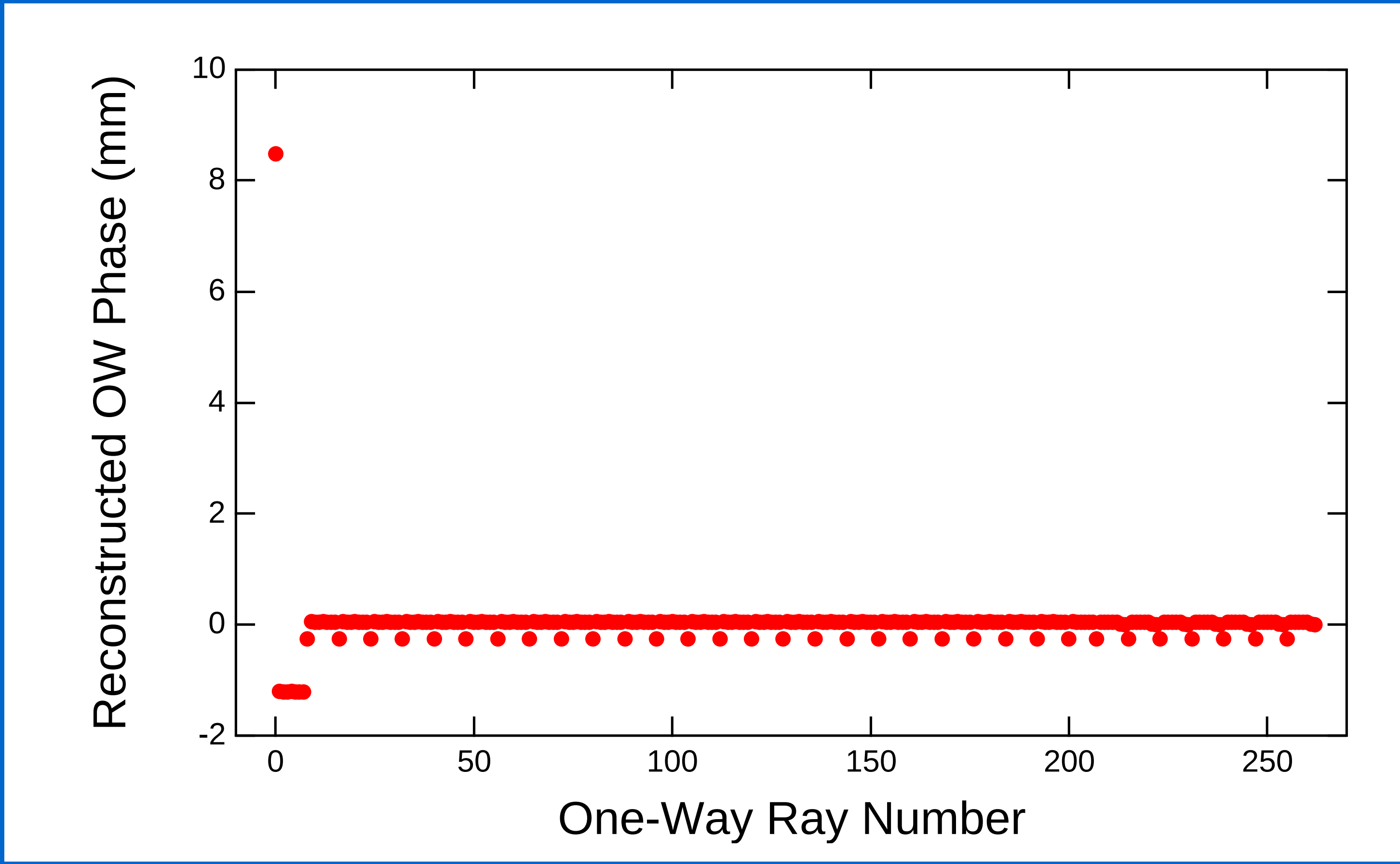
Unwrap Double-Difference Residuals



One-way phase residuals reflect the spreading, by the (here physically incorrect) “zero-mean” assumption, over all rays of the 10 mm anisotropy mapped into the double-difference residuals. Indeed, non-zero rays are those that involve site and satellite 1.

Reconstruct Atmosphere

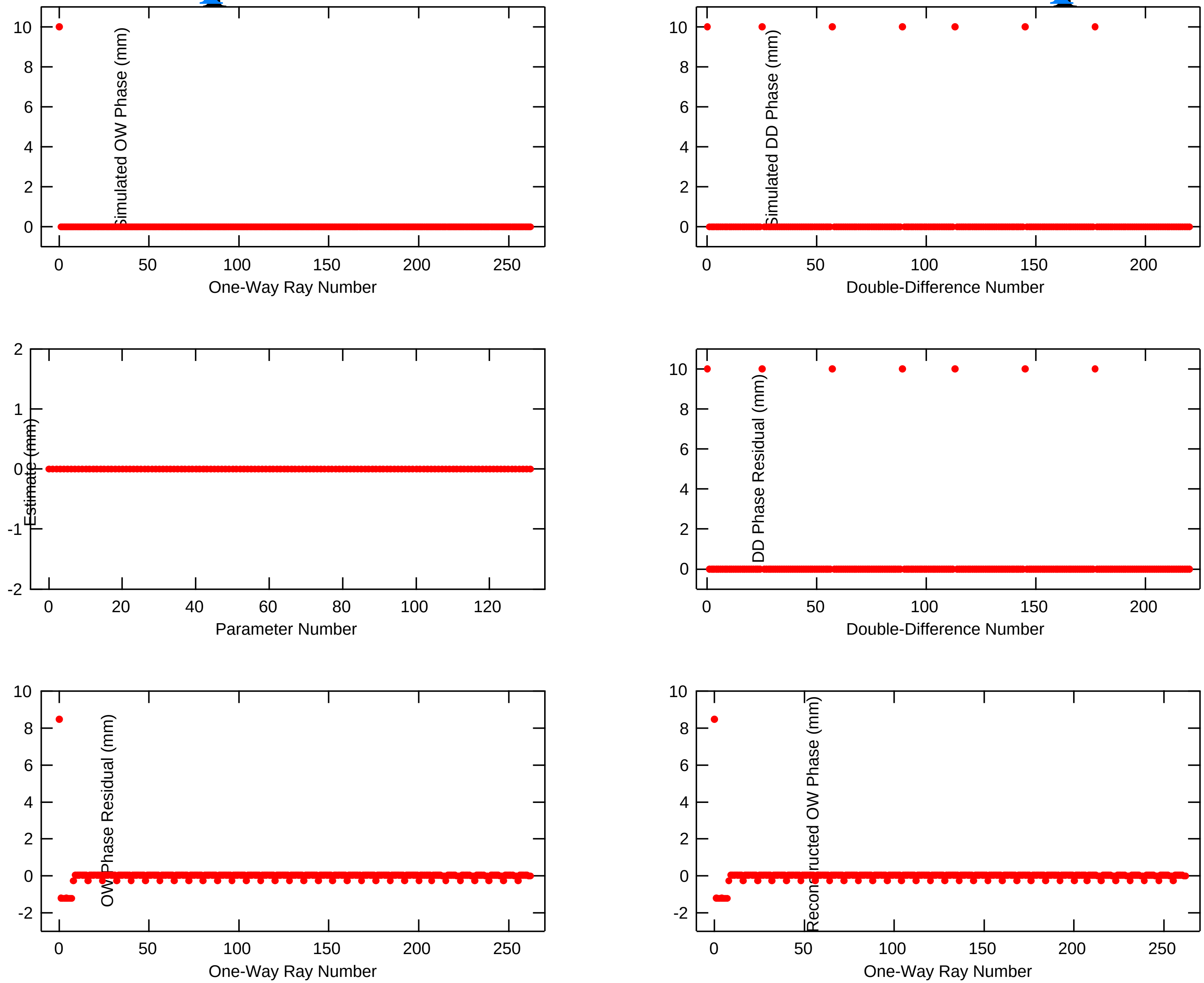
III



The reconstructed one-way phases are the one-way phase residuals because the estimated atmospheric parameters are zero mm. Site ARM1 reconstructs 9.7 of the 10 mm difference between Ray 0 and the other rays.

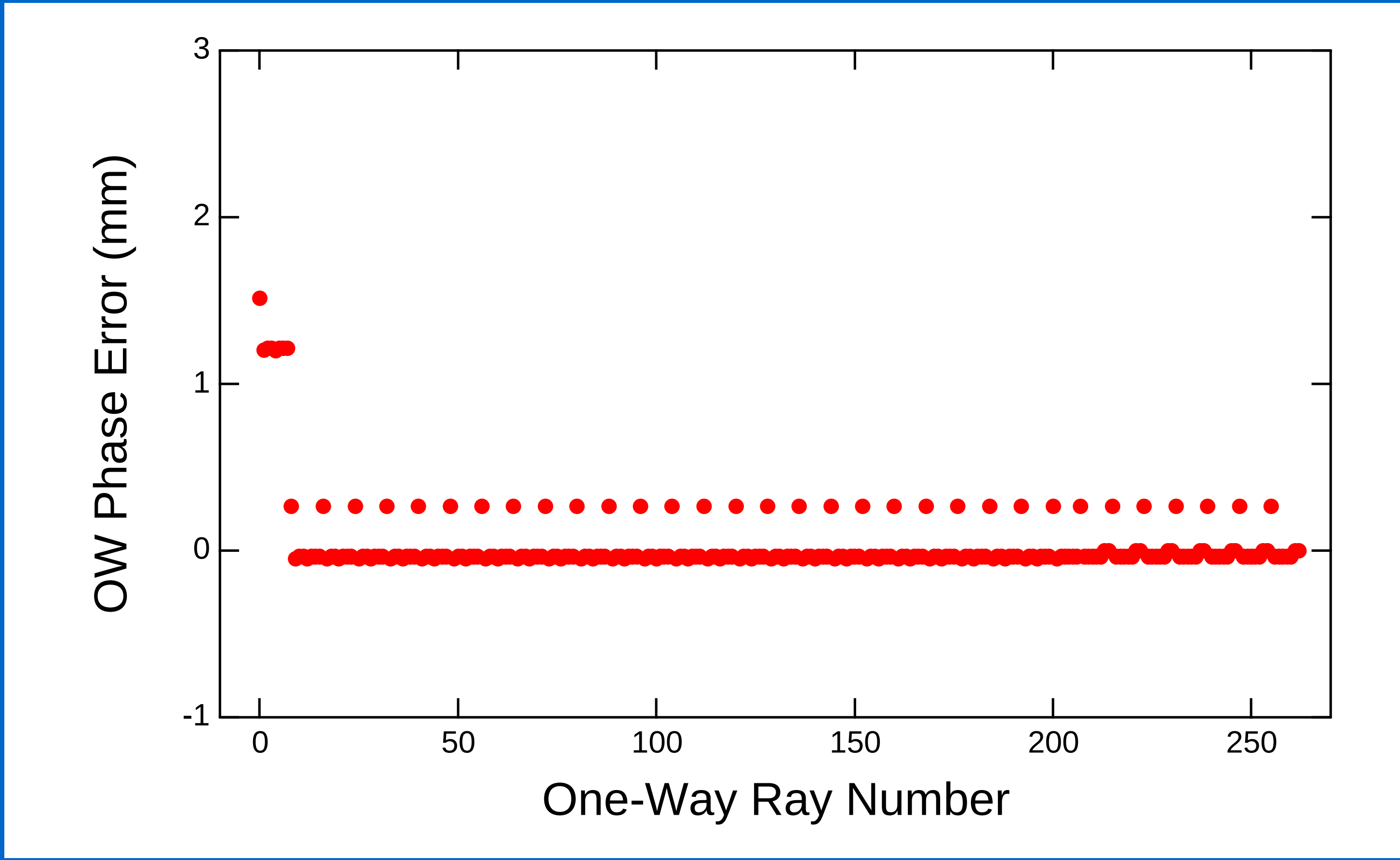
Composite of Previous Graphs

III



Compare Simulated and Reconstructed Atmospheres

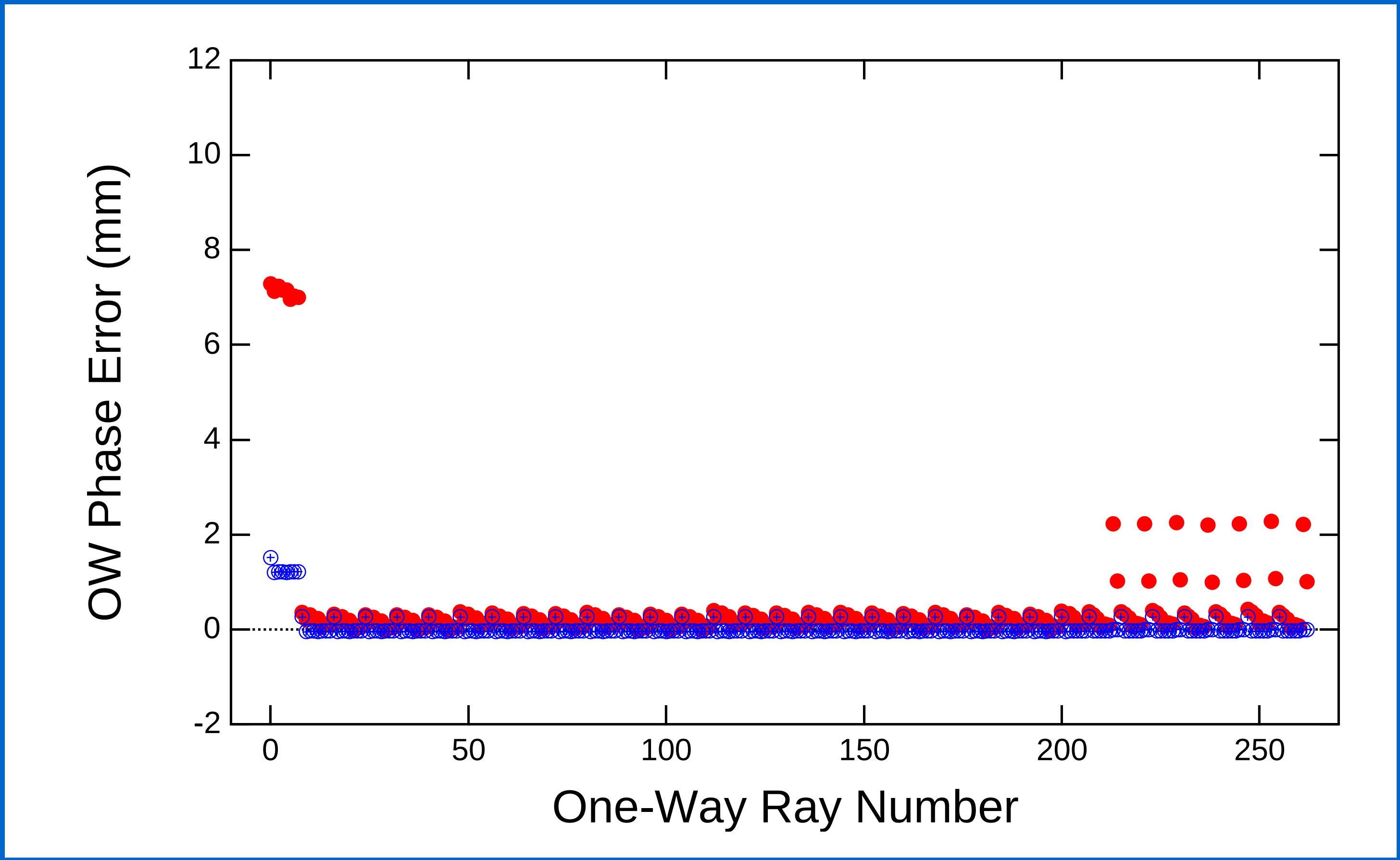
III



The reconstructed one-way phases at ARM1 are in error by a maximum of 1.5 mm. Largest error for other phases amounts to ~0.3 mm. The RMS of the reconstructed one-way phases is 0.24 mm (0.10 mm if ARM1 phases are not considered).

Compare Reconstructions

III



Reconstruction errors of the standard method (red) are significantly larger than those that result when external constraints on the atmospheric parameters estimated in the least-squares are used (blue). The error of the latter, though significantly smaller, represents 15% of the signal that we are trying to measure. The RMS error of the reconstruction has improved from 1.3 mm to 0.2 mm.

Summary of Simulation III

III

- When atmospheric parameters tightly constrained to their true value are used in the least-squares step:
  - Errors amount to ~1.5 mm of phase, compared to ~7 mm, for all one-way observations at the site that observed the single 10 mm anisotropy.
  - Errors amount to 0.3 mm, compared to ~2 mm, at the sites that did not observed the anisotropy.
  - The RMS error of the reconstruction is 0.2 mm, as opposed to 1.3 mm.

- Despite the significant improvement in "accuracy" and "precision" of the standard method when external constraints are used, the reconstruction error still represents ~15% of the signal that we are trying to measure.

- This ~15% error is due to the *Albers et al.* [2000] unwrapping algorithm because the "zero-mean" is not an assumption that is physically correct.

- The availability of external constraints on atmospheric parameters at the 0.001 mm level would render this GPS approach unnecessary.

Additional Simulations

- Homogenous atmosphere except that a single anisotropy is common to two satellites at a particular site
- Same as A except that the single anisotropy is common to several regional sites in the direction of a particular satellite
- Same as B, but both the common anisotropy and the simulation last 15 minutes, instead of a single epoch

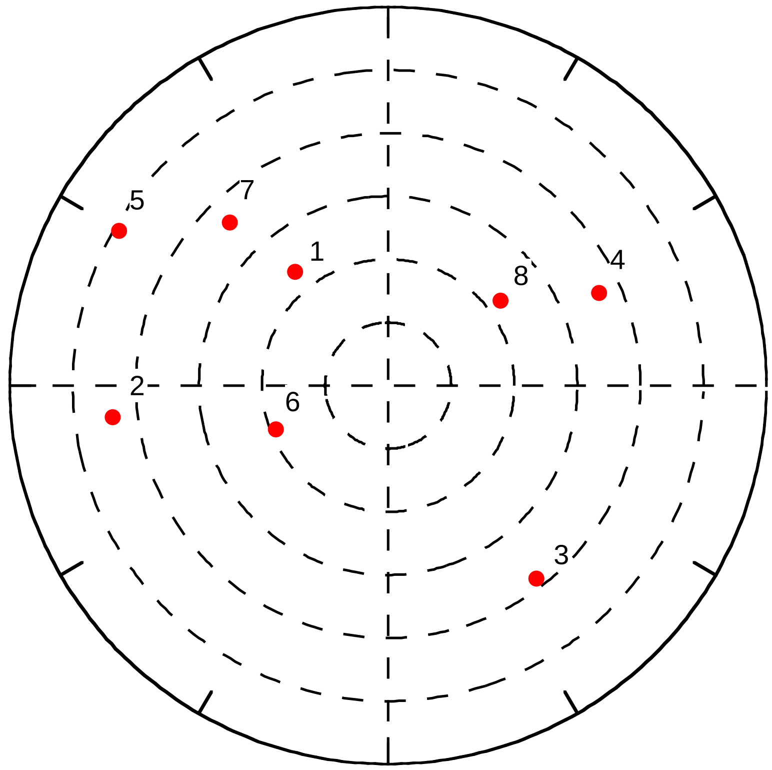
A

Simulation A

Simulated atmosphere is perfectly homogenous except for an anisotropy of 10 mm of phase localized along the line-of-sight to two satellites from a site.

These observing conditions may arise if an anisotropy is close to the ground and cover a significant part of the sky as seen from a site. The purpose of this simulation is to explore the possibility of accuracy improvement using the standard method by some sort of spatial cancellation of common anisotropies.

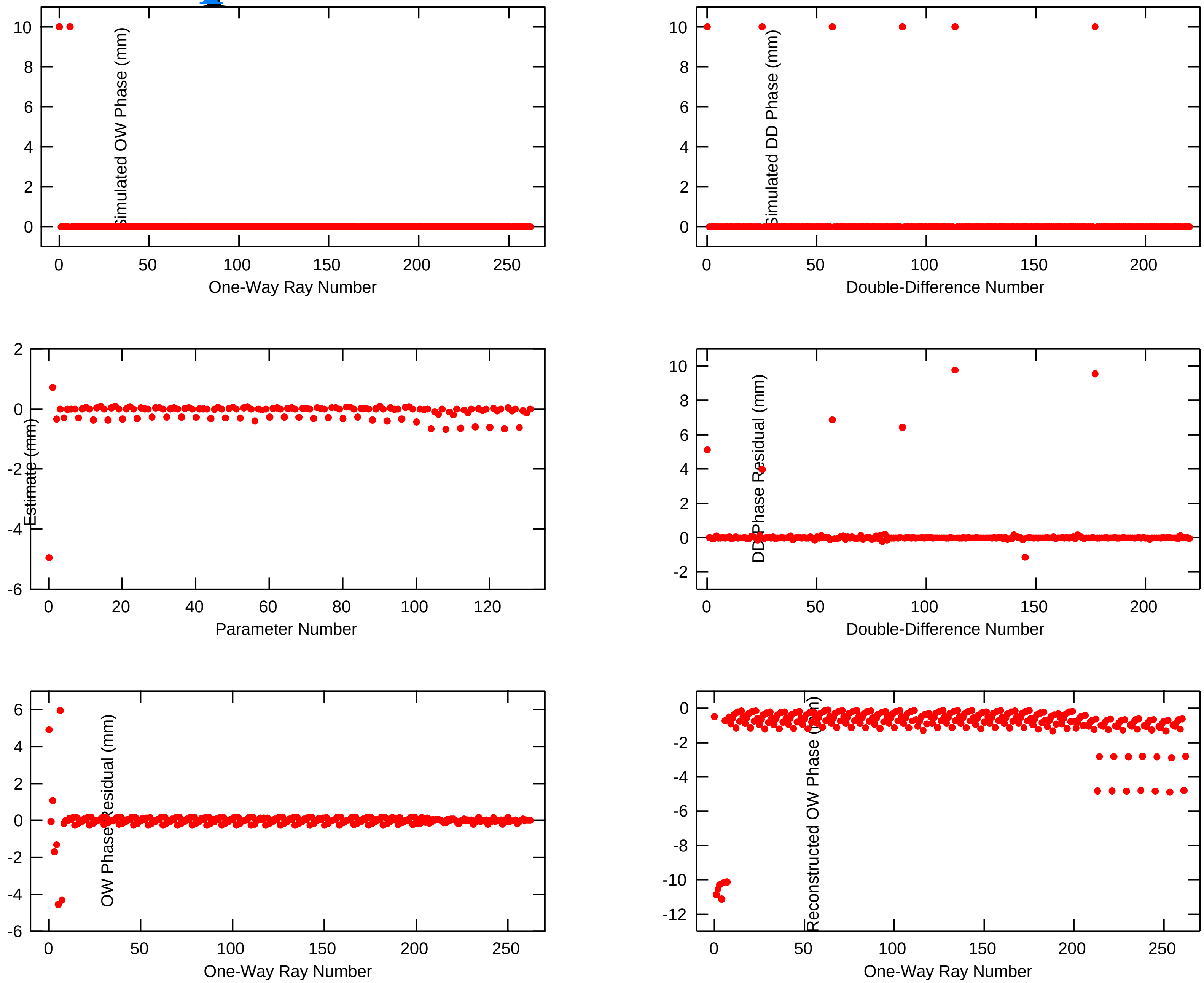
Geometry of Simulation A



We will perform two simulations. In the first, the anisotropy will affect the line-of-sights to satellites 1 and 7; in the second, to satellites 4 and 8. The angular separation of both pairs are ~15º. (Although we have not explored all possible pair combinations, we assume that these two pairs represent adequately the purpose of this simulation.)

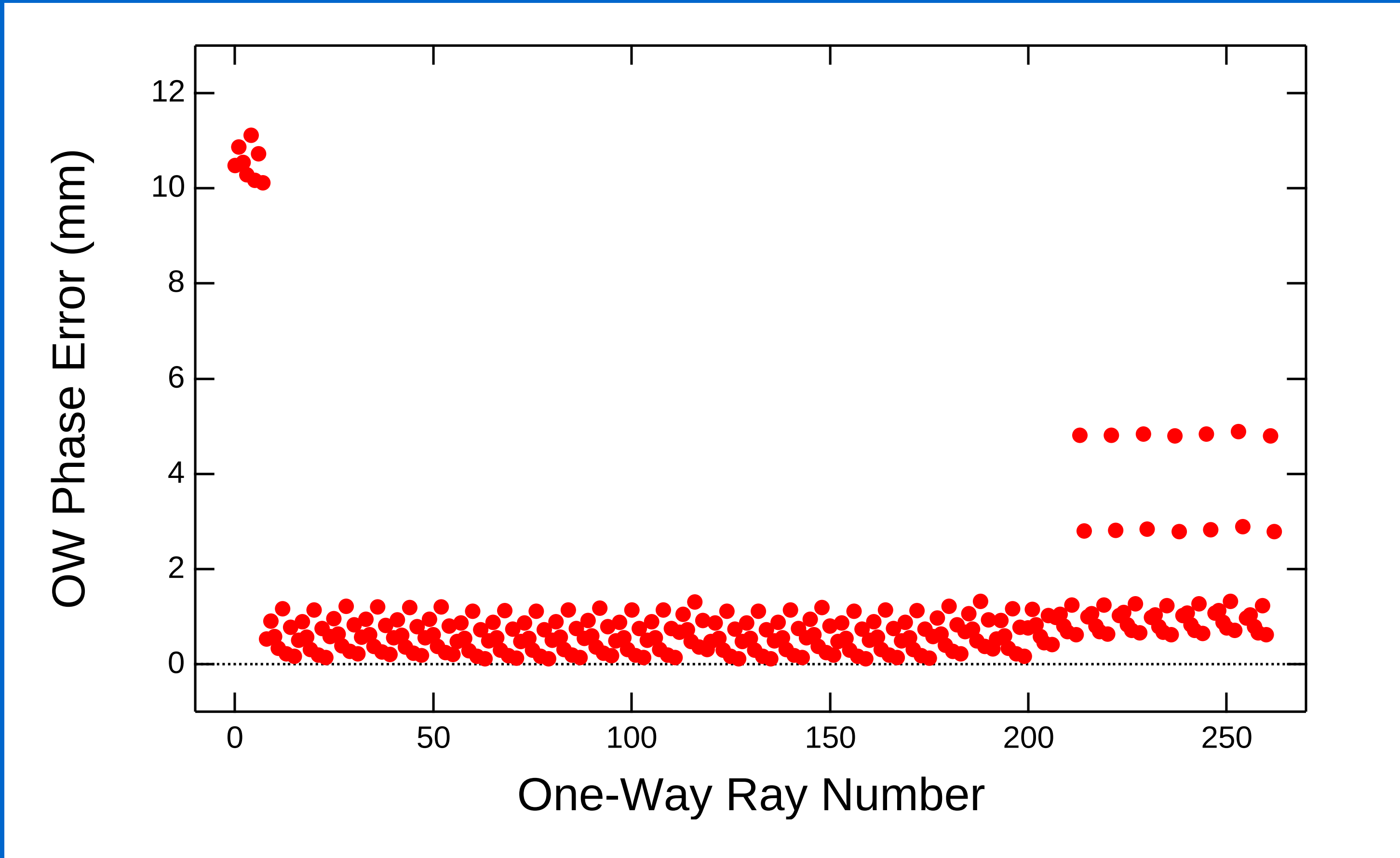
Composite of Satellites 1 and 7

A



Compare Simulated and Reconstructed Atmospheres

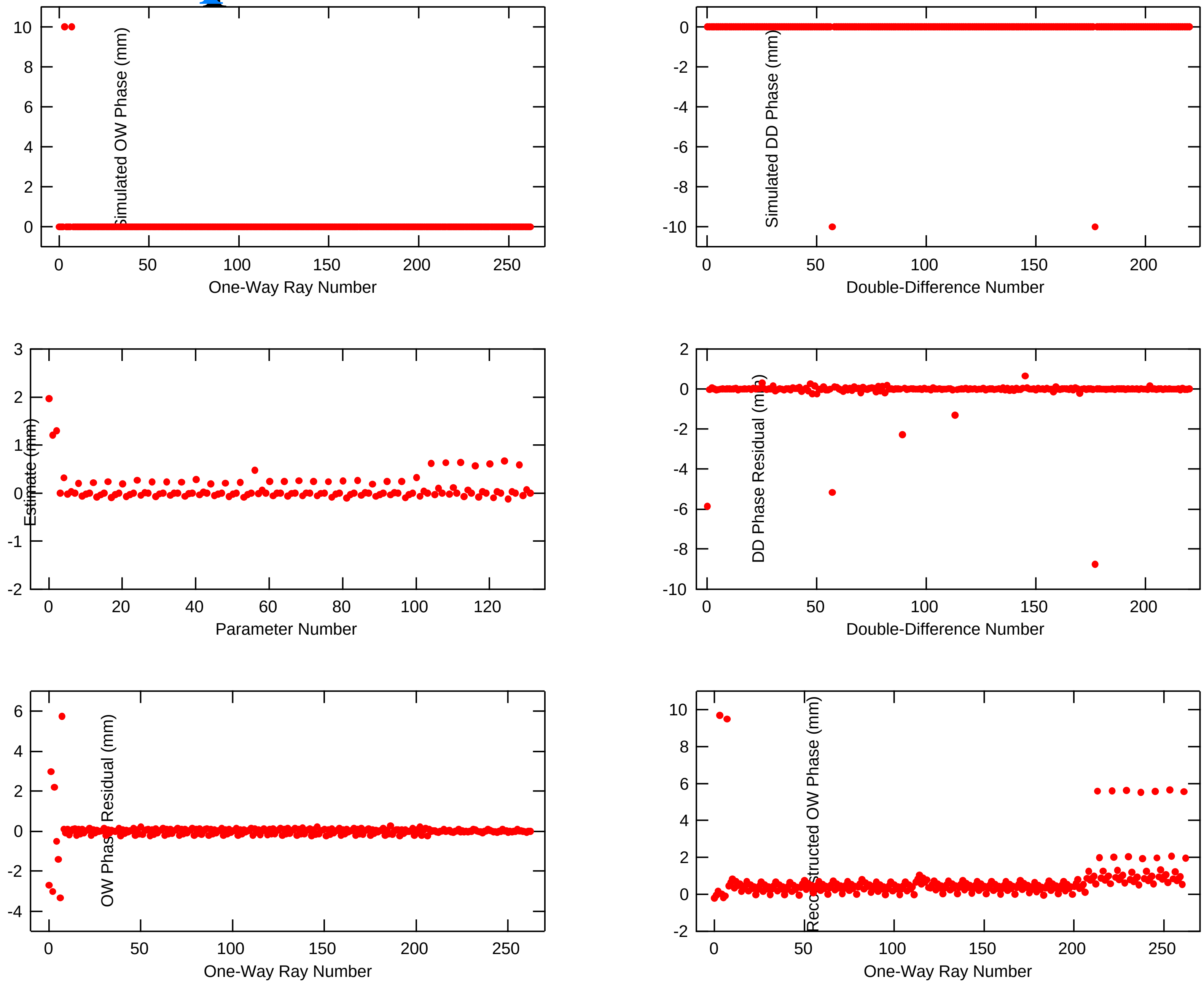
A



All reconstructed one-way phases at the site that observed the 10 mm common anisotropy are in error by ~10 mm. Largest error for other rays amounts to ~5 mm.

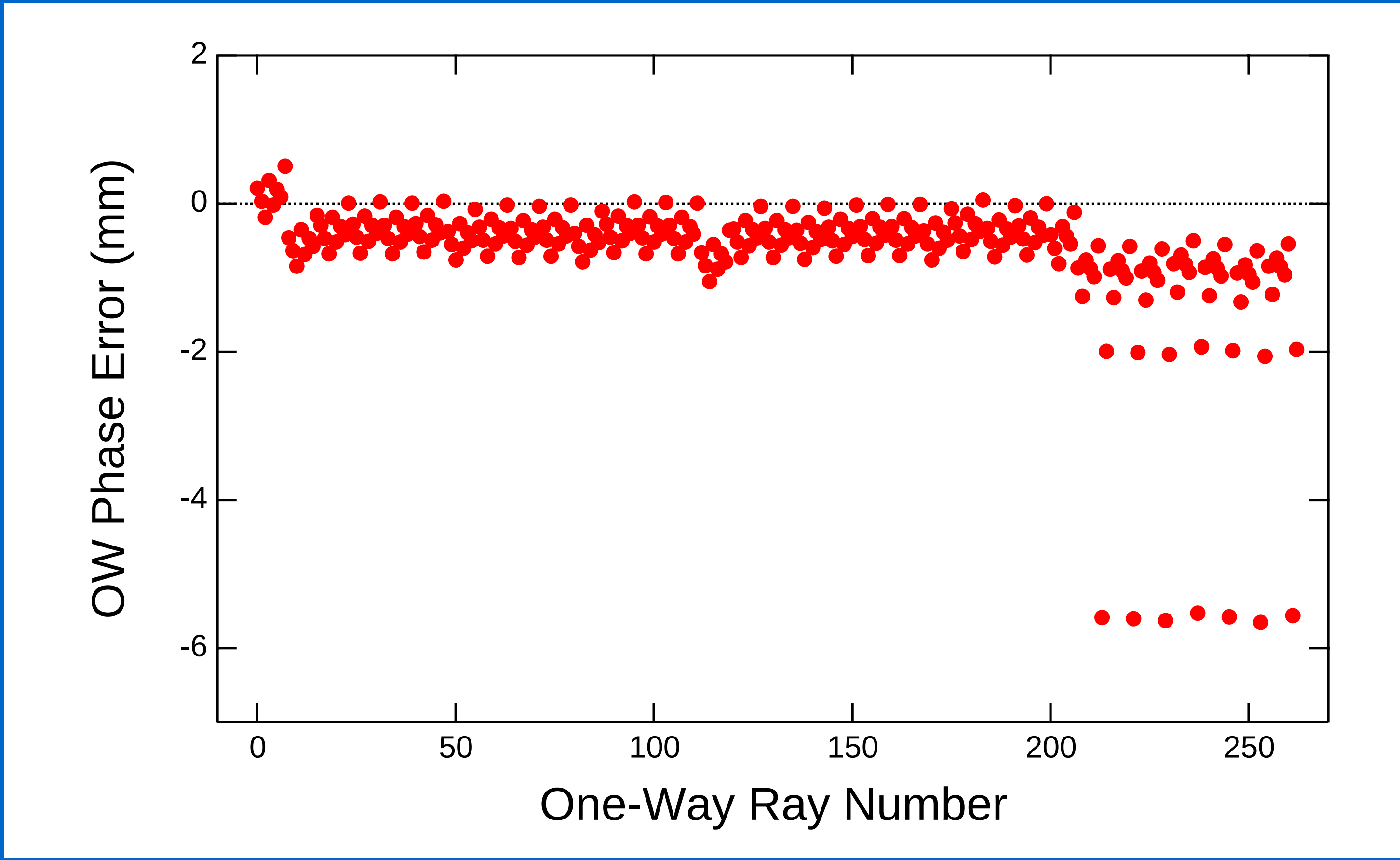
Composite of Satellites 4 and 8

A



Compare Simulated and Reconstructed Atmospheres

A



All reconstructed one-way phases at the site that observed the 10 mm anisotropy are reconstructed correctly (fraction of a mm). Reconstructed phases at all other sites are in error by up to ~6 mm.

A

Summary of Simulation A

- Most reconstructed one-way observations are biased.
- For the two observing geometries simulated, errors vary between 0–100% of the signal that we are trying to measure.
- Errors amount up to ~6 mm of phase at the other sites.
- Configurations involving common anisotropies do not result in an improvement in the accuracy of the reconstructed slant wet delay using the standard method.

B

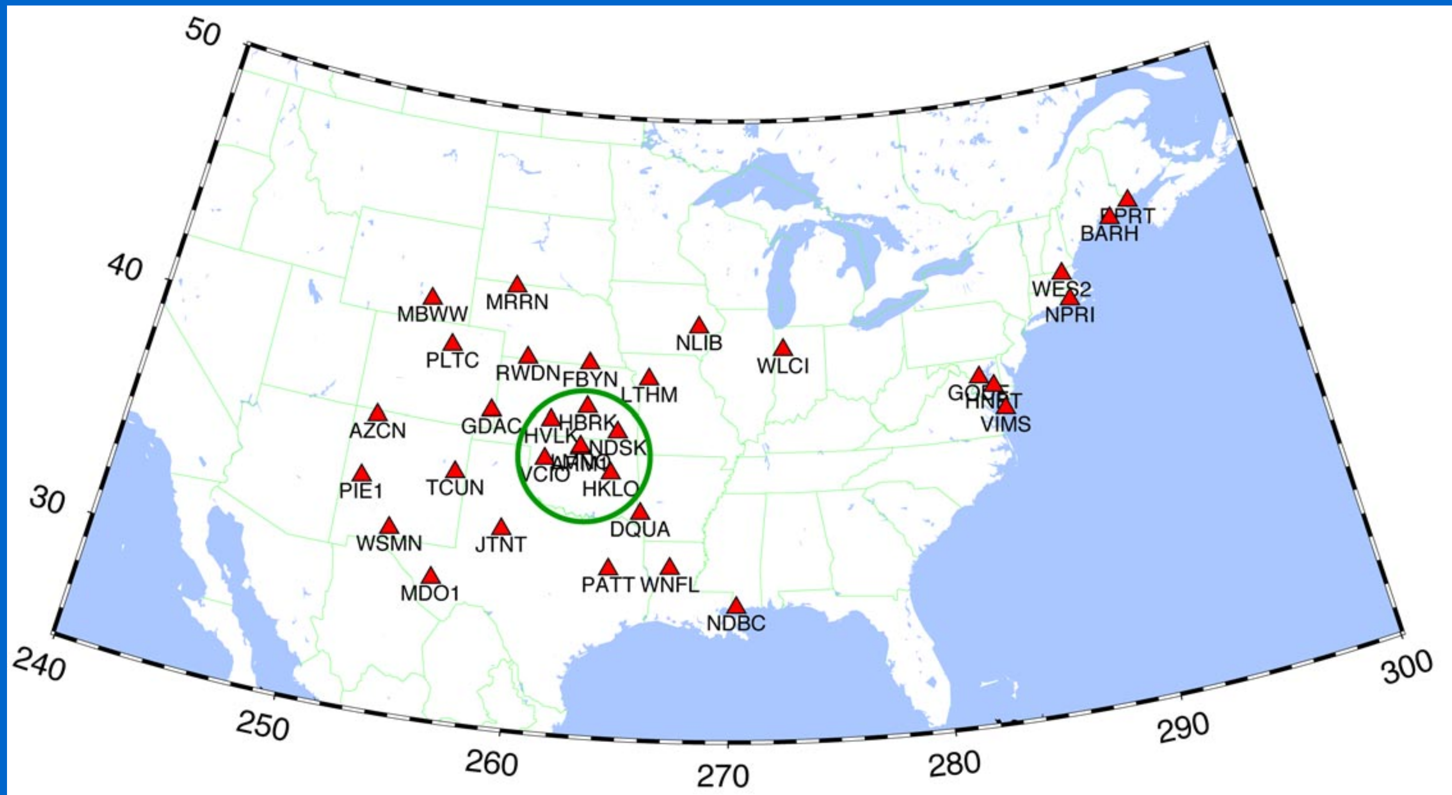
Simulation B

Simulated atmosphere is perfectly homogenous except for a localized anisotropy of 10 mm of phase in the direction of a particular satellite from a subset of regional sites.

The purpose of this simulation is to further explore the possibility of accuracy improvement using the standard method by some sort of spatial cancellation of common anisotropies.

B

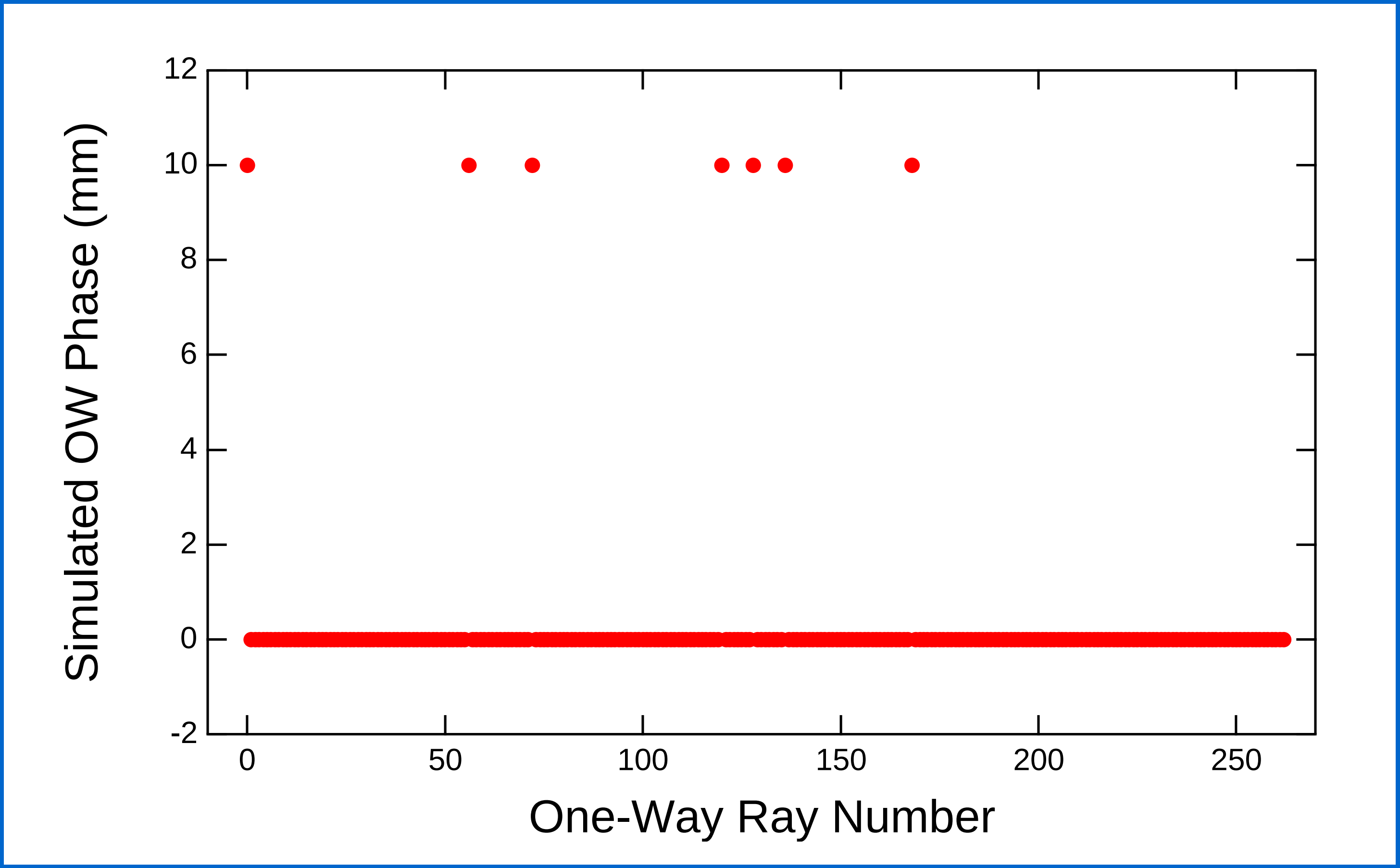
Ground-based GPS Network



The common anisotropy will be observed by the seven encircled sites, which are within 200 km radius of site ARM1.

Simulate Atmosphere

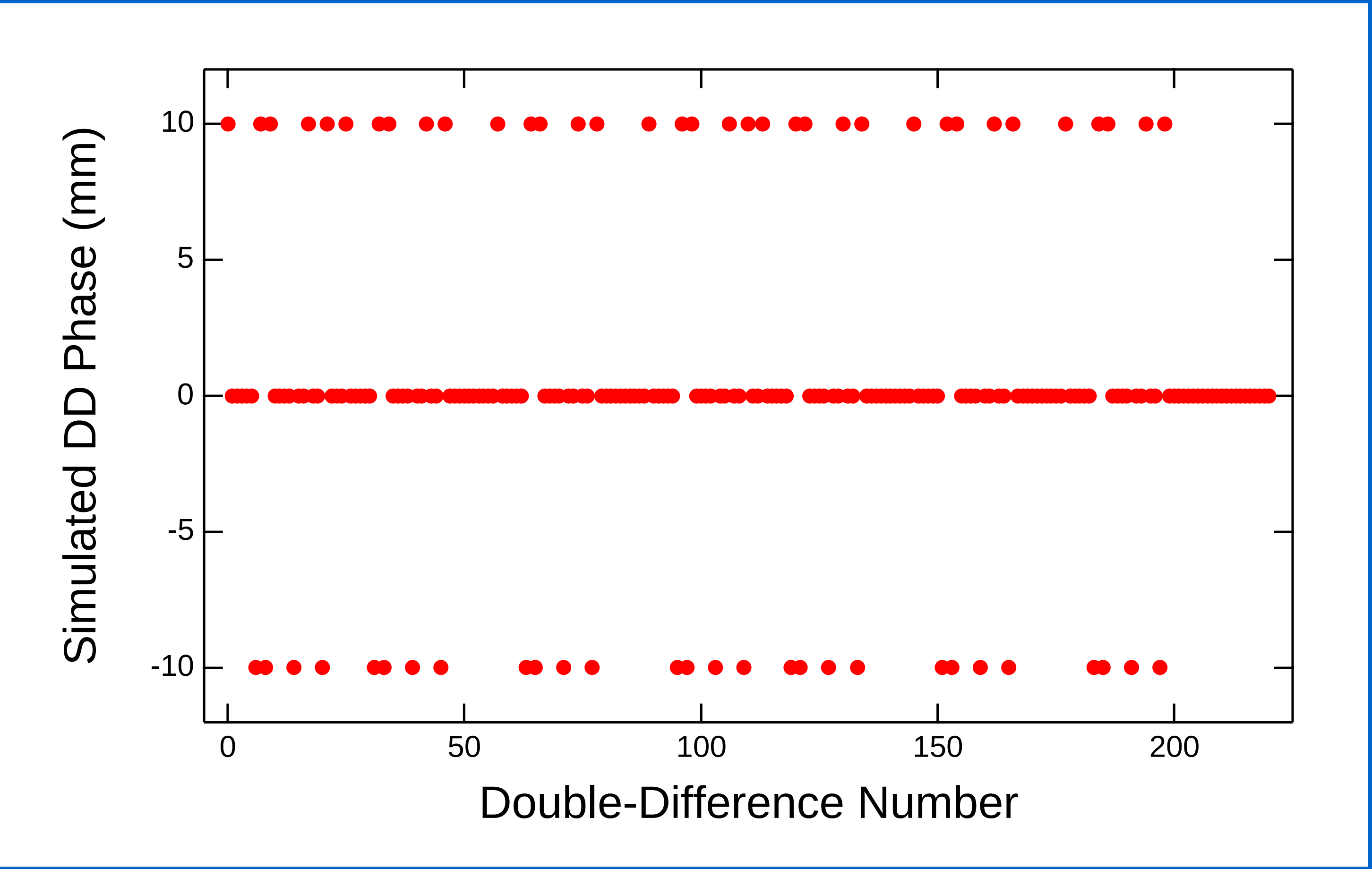
B



Simulated atmosphere is zero mm for all one-way phases but for the rays from a satellite (PRN 21) to all sites within 200 km of site ARM1. The anisotropy represented by Rays 0, 56, 72, 120, 128, 136, and 168 amount to 10 mm of one-way phase.

Form Double Differences

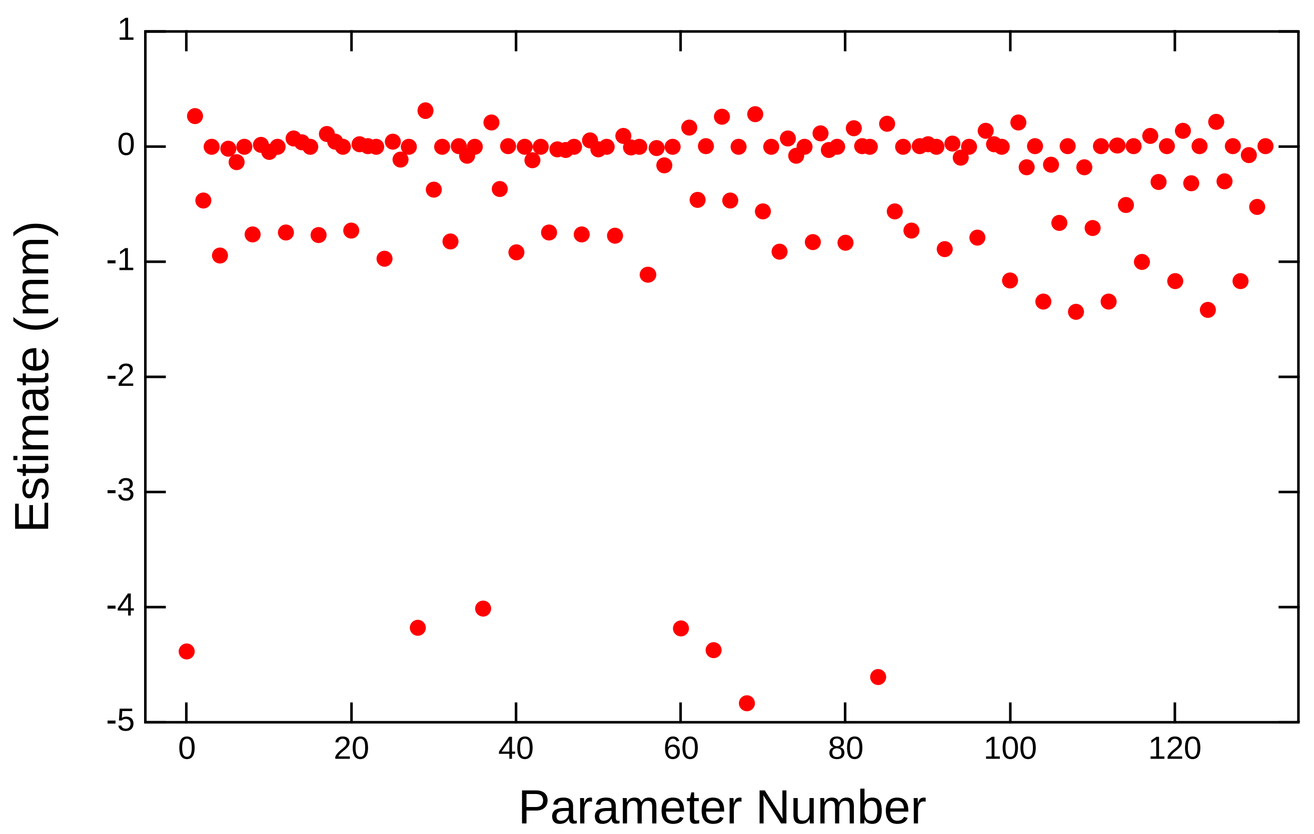
B



Simulated atmosphere results in zero mm for all double-difference phases but for those that involve rays to satellite PRN 21 from sites near ARM1, which are ±10. The sign depends on the order in which the ray with the anisotropy enters the double-difference. When two “anisotropy rays” form a double-difference, the phase is also zero (cancel).

Perform Least Squares

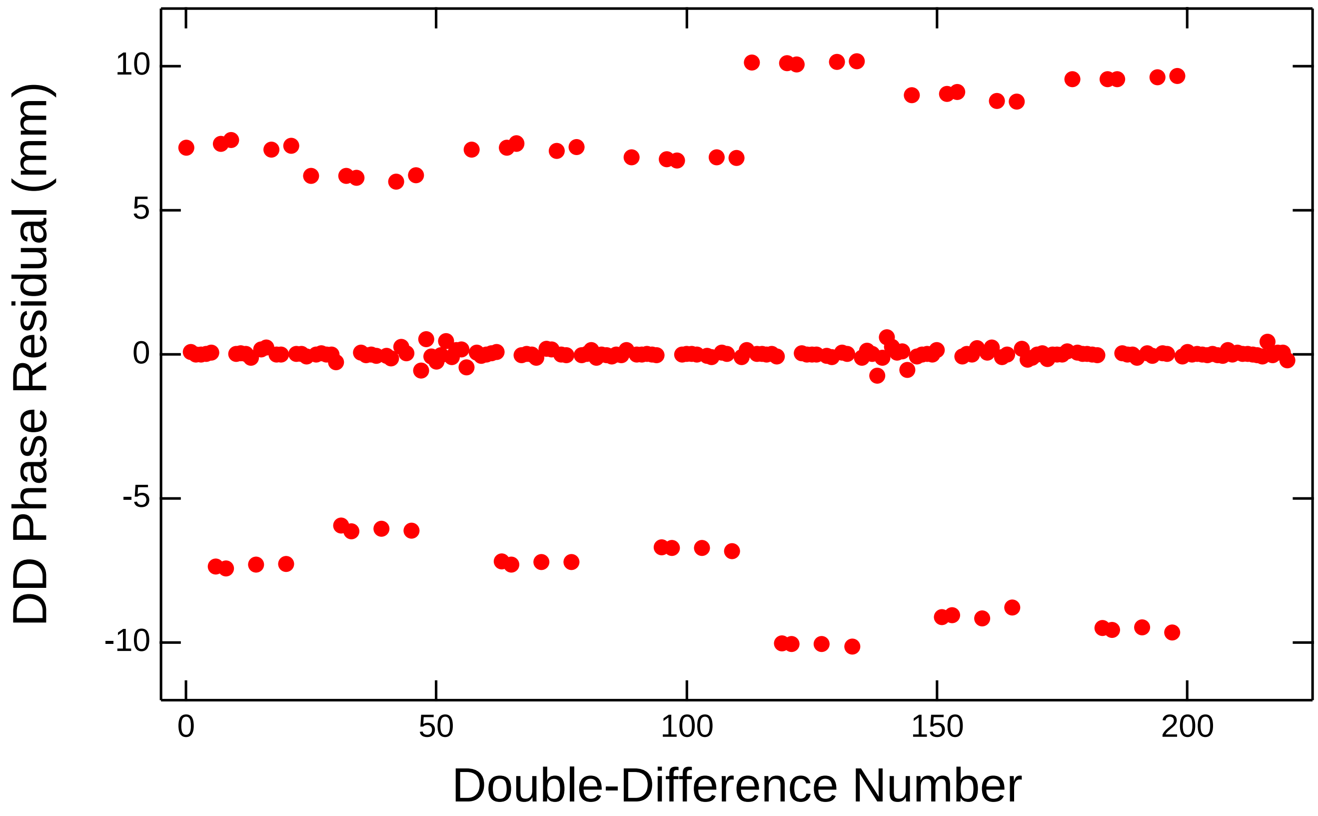
B



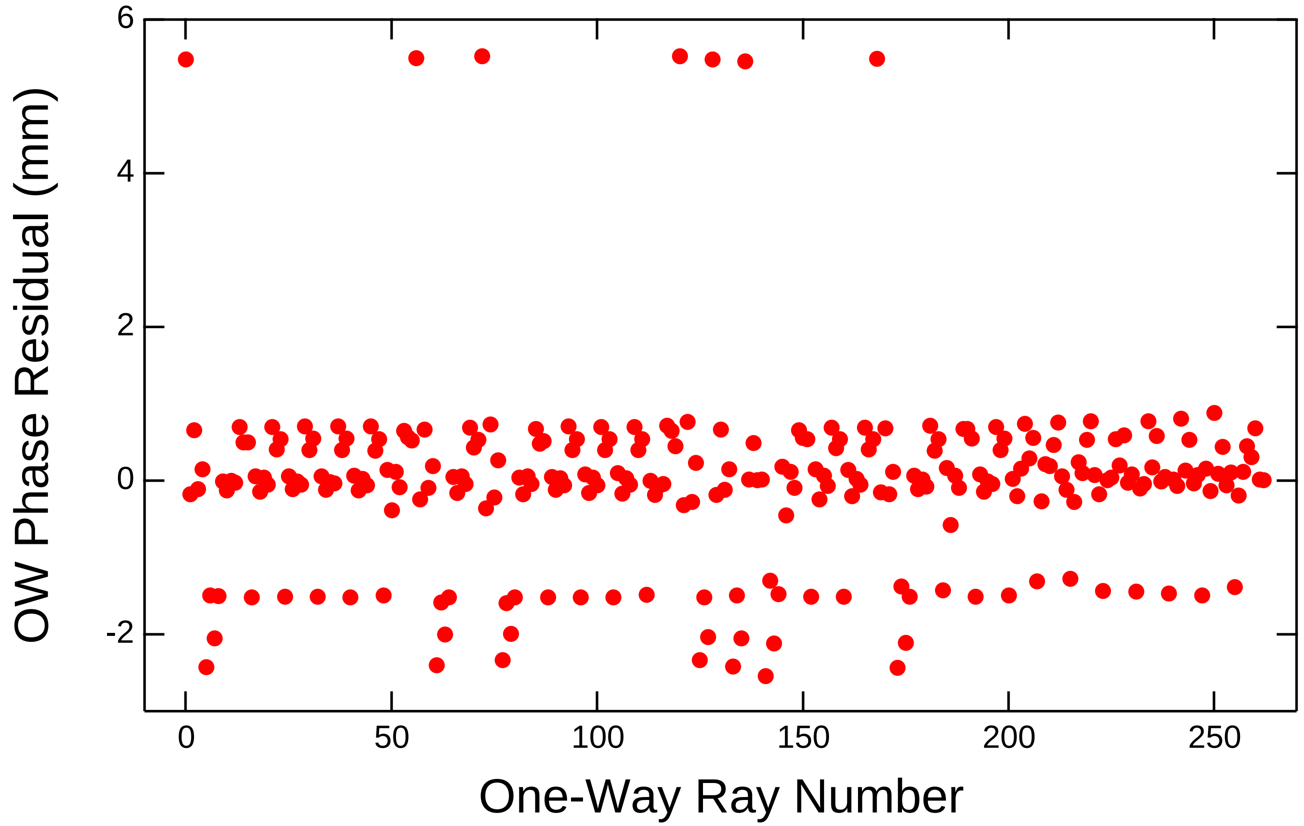
Least squares modeled the ±10 mm anisotropy as an adjustment to all atmospheric parameters of all sites. The seven sites absorb the anisotropy via the zenith delay (4-5 mm), the north (~0.2 mm) and the east (~0.4 mm) gradient. The zenith delay of all other sites is affected at the ~1 mm level, with the distant sites shown the largest values. The gradient parameters, especially the east, are also affected at the 0.2–0.7 mm level.

Calculate Double-Difference Residuals

B

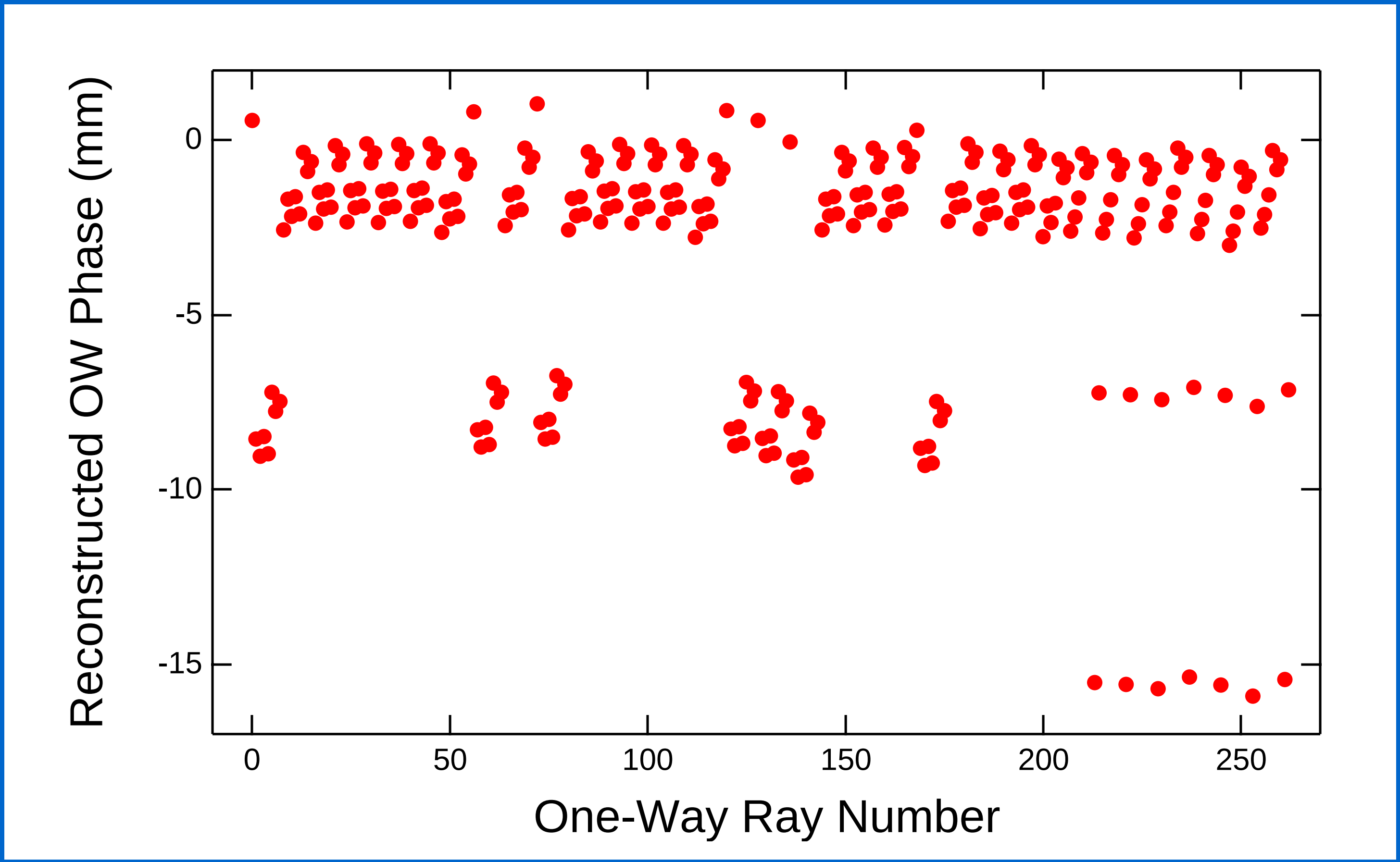


Unwrap Double-Difference Residuals



Reconstruct Atmosphere

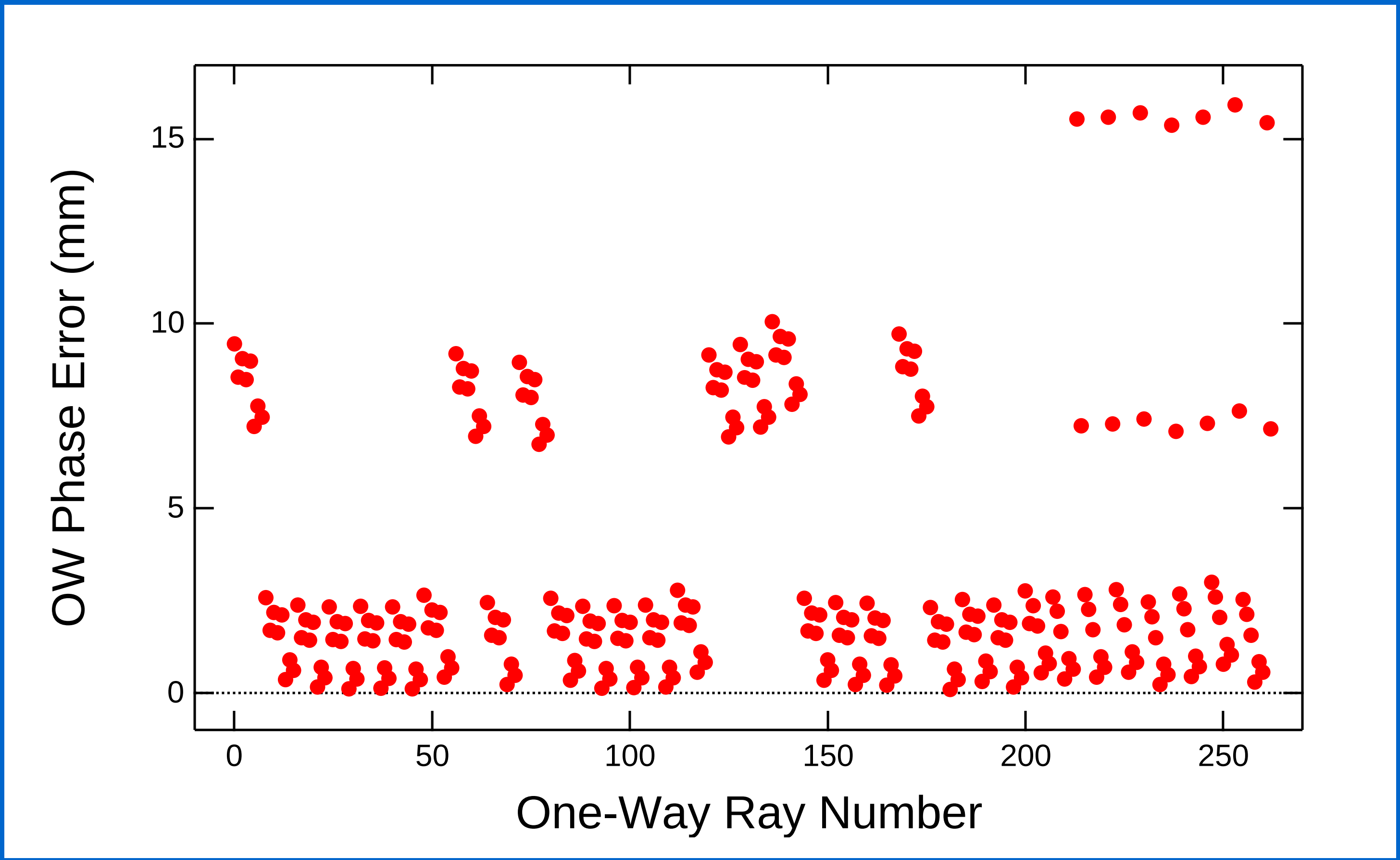
B



All seven regional sites recover 8–9 mm of the 10 mm difference between the anisotropy ray and the rest of rays, but all its reconstructed phases are biased. The reconstructed phases of all other sites are also biased at the <~3 mm level, except for the distant sites, which for the low elevation-angle satellites, show biases at the ~7 and ~15 mm level.

Compare Simulated and Reconstructed Atmospheres

B



All reconstructed one-way phases at the sites that observed the 10 mm common anisotropy are in error by ~7–10 mm. Errors introduced by the double-difference algorithm are larger than the 10 mm anisotropy that we are trying to measure.

Summary of Simulation B

B

- All reconstructed one-way observations are biased.
- Errors amount to ~7–10 mm of phase for all one-way observations at all seven sites that observed the single 10 mm common anisotropy.
- Errors amount up to ~3 mm of phase at all sites that do not observe the anisotropy but are within <~1000 km of site ARM1.
- Errors amount up to ~16 mm of phase at the far distant sites, larger than the 10 mm common anisotropy signal that we are trying to detect.
- Configurations involving common anisotropies do not result in an improvement in the accuracy of the reconstructed slant wet delay.

Simulation C

C

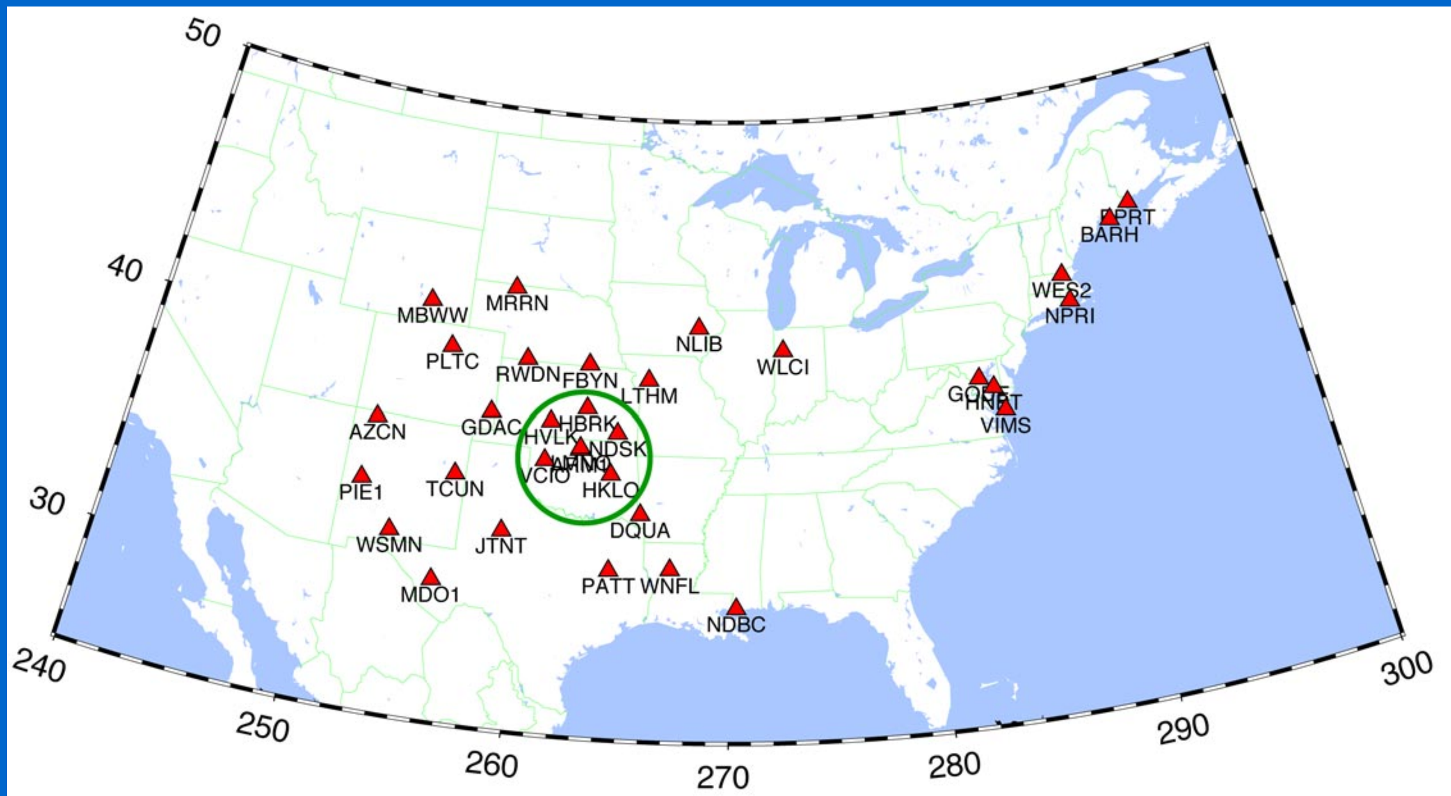
Simulated atmosphere is perfectly homogenous except for a localized anisotropy of 10 mm of phase in the direction of a particular satellite from a subset of regional sites.

The anisotropy and the simulation both last 15 minutes. The atmosphere is sampled once every 30 seconds. The observations are assumed to be uncorrelated between consecutive epochs.

Similar to simulation B but with observations accumulated over 15 minutes instead of one single epoch. This simulation is performed to explore the possibility of spatio-temporal cancellation by spreading the common-view anisotropies over more observations.

C

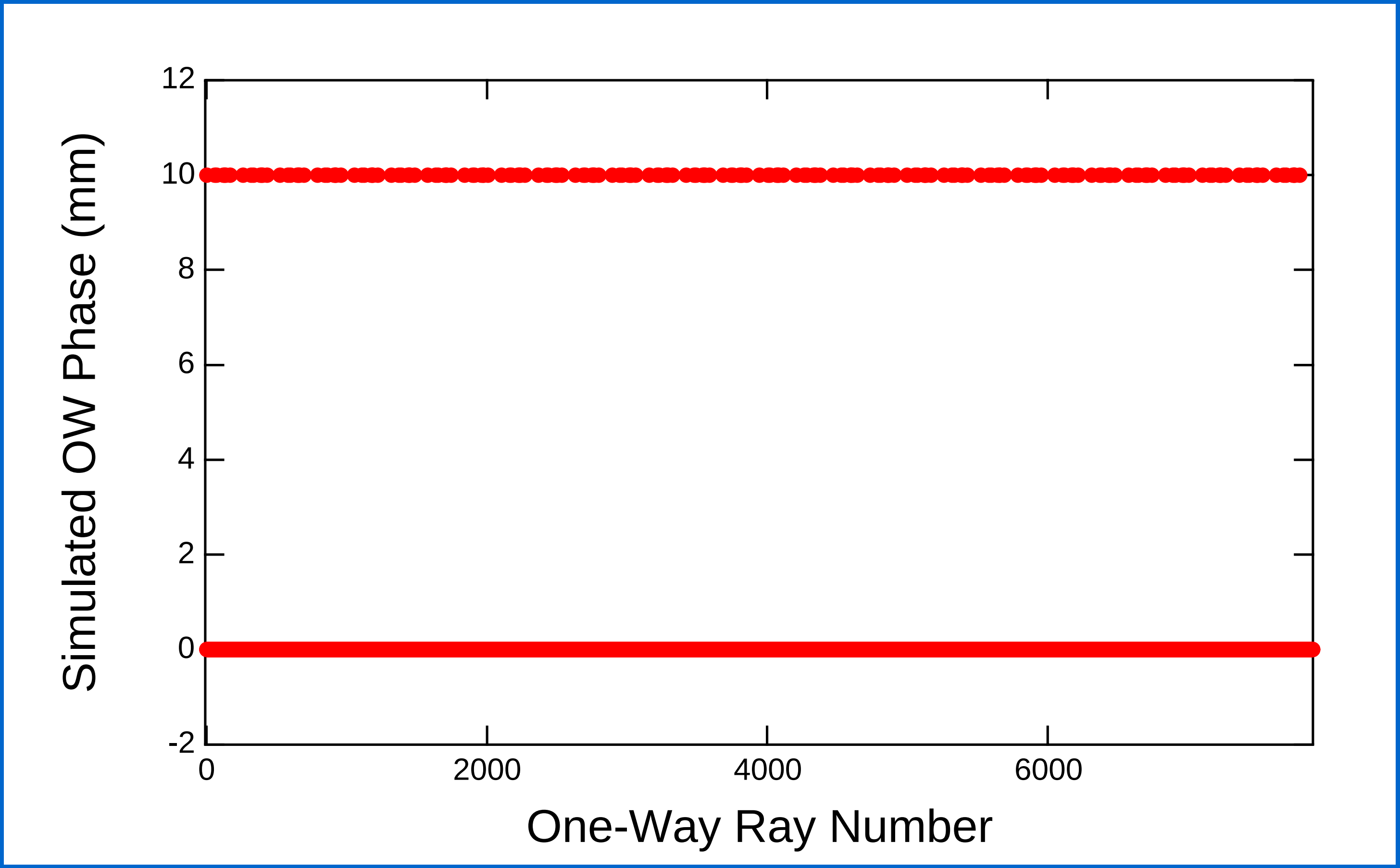
Ground-based GPS Network



The common anisotropy will be observed by the seven, 200-km radius encircled sites, and will last 15 minutes.

Simulate Atmosphere

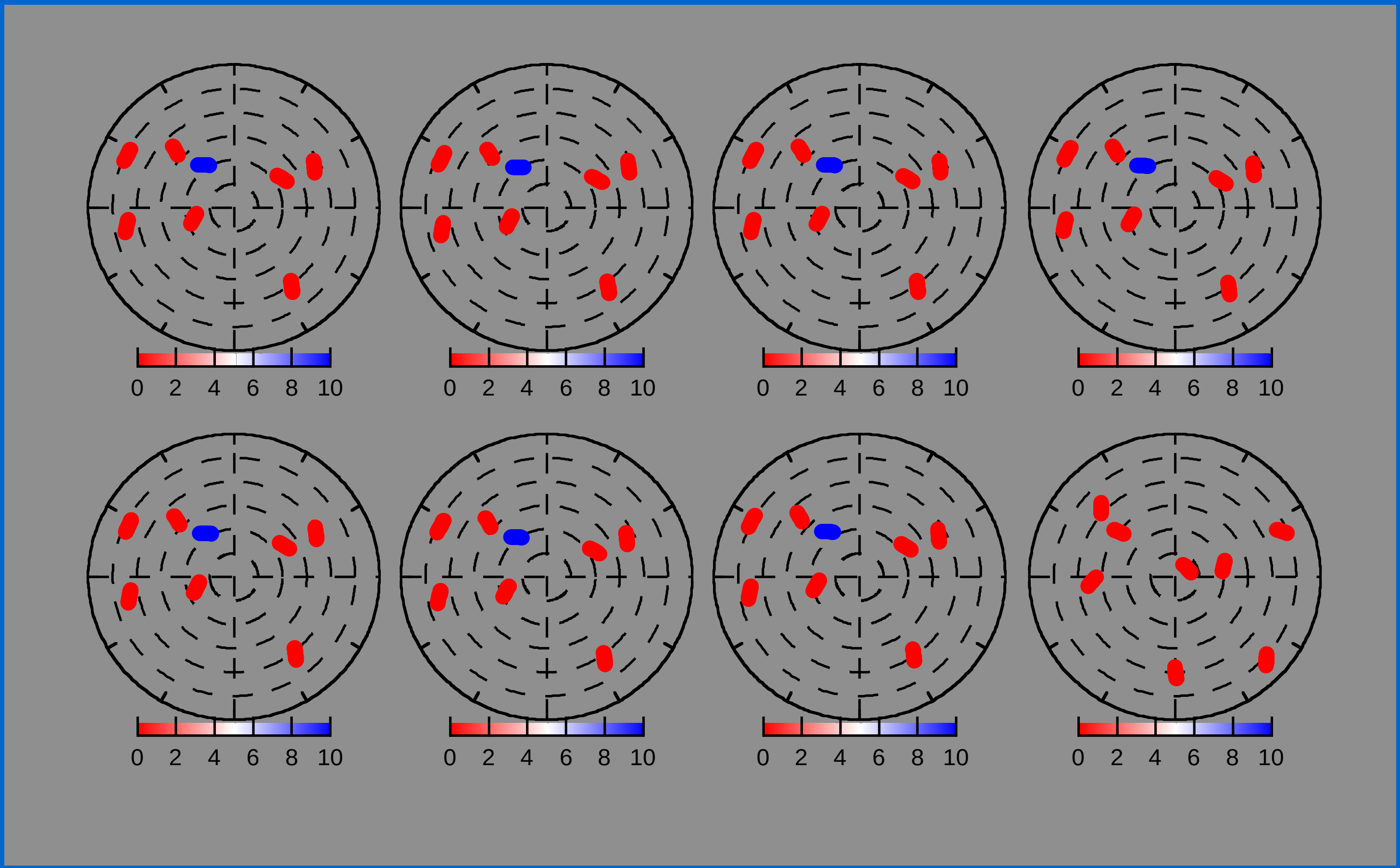
C



Simulated atmosphere is zero mm for all one-way phases but for the rays from a satellite (PRN 21) to all sites within 200 km of site ARM1. There are a total of 7890 rays, 210 (~3%) of which observe the 10 mm one-way phase anisotropy. The atmosphere is sampled once every 30 seconds during 15 minutes.

Simulate Atmosphere

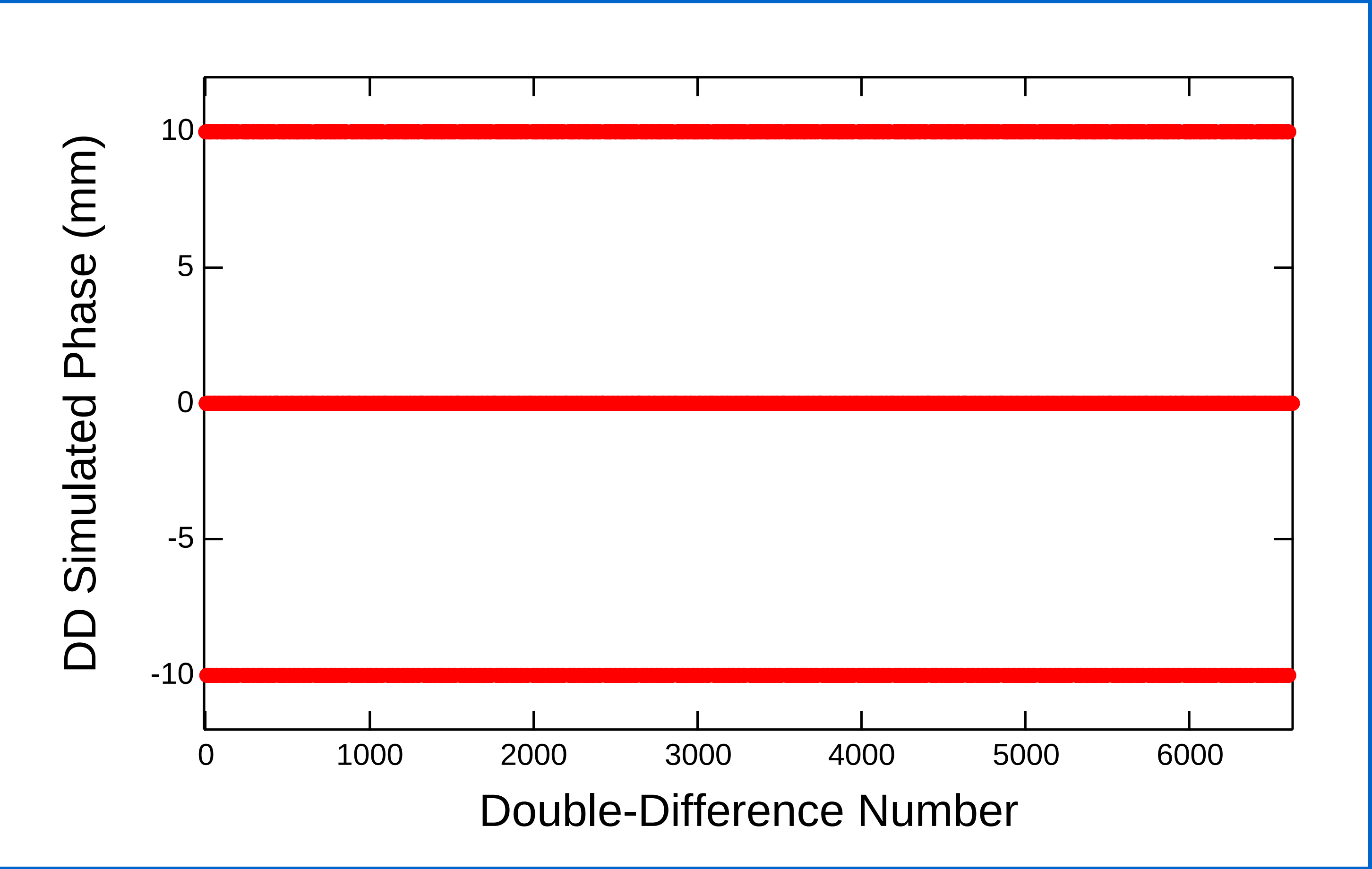
C



Common anisotropy of 10 mm one-way phase (blue) observed at the seven local sites. Each satellite track lasts 15 minutes. There is one new observation every 30 seconds. The remaining 24 sites observed an homogenous atmosphere, an example of which is shown by the distant WES2 site at the bottom-rightmost sky plot.

Form Double Differences

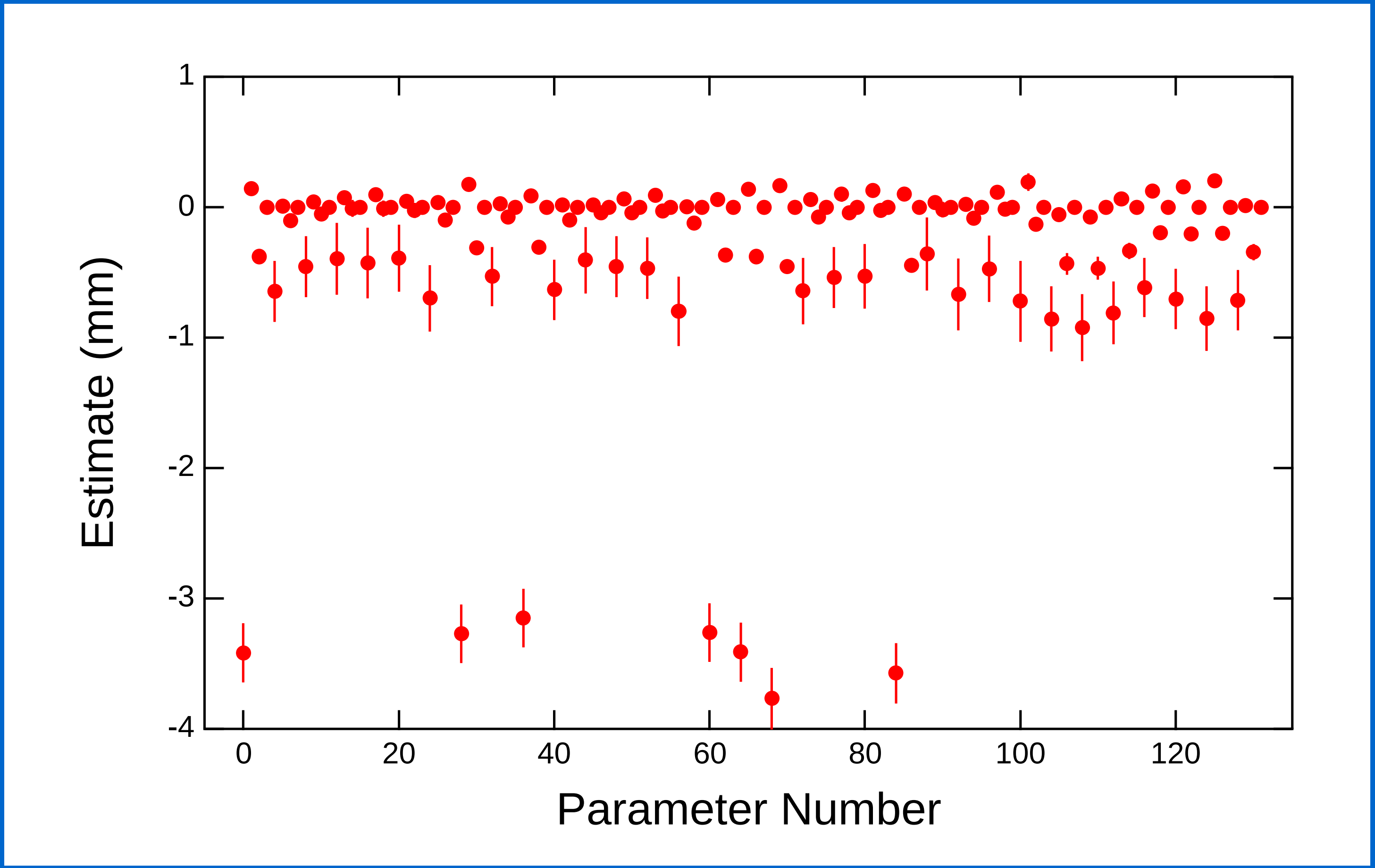
C



Simulated atmosphere results in zero mm for all double-difference phases but for those that involve rays to satellite PRN 21 from the seven regional sites, which are ±10 mm.

Perform Least Squares

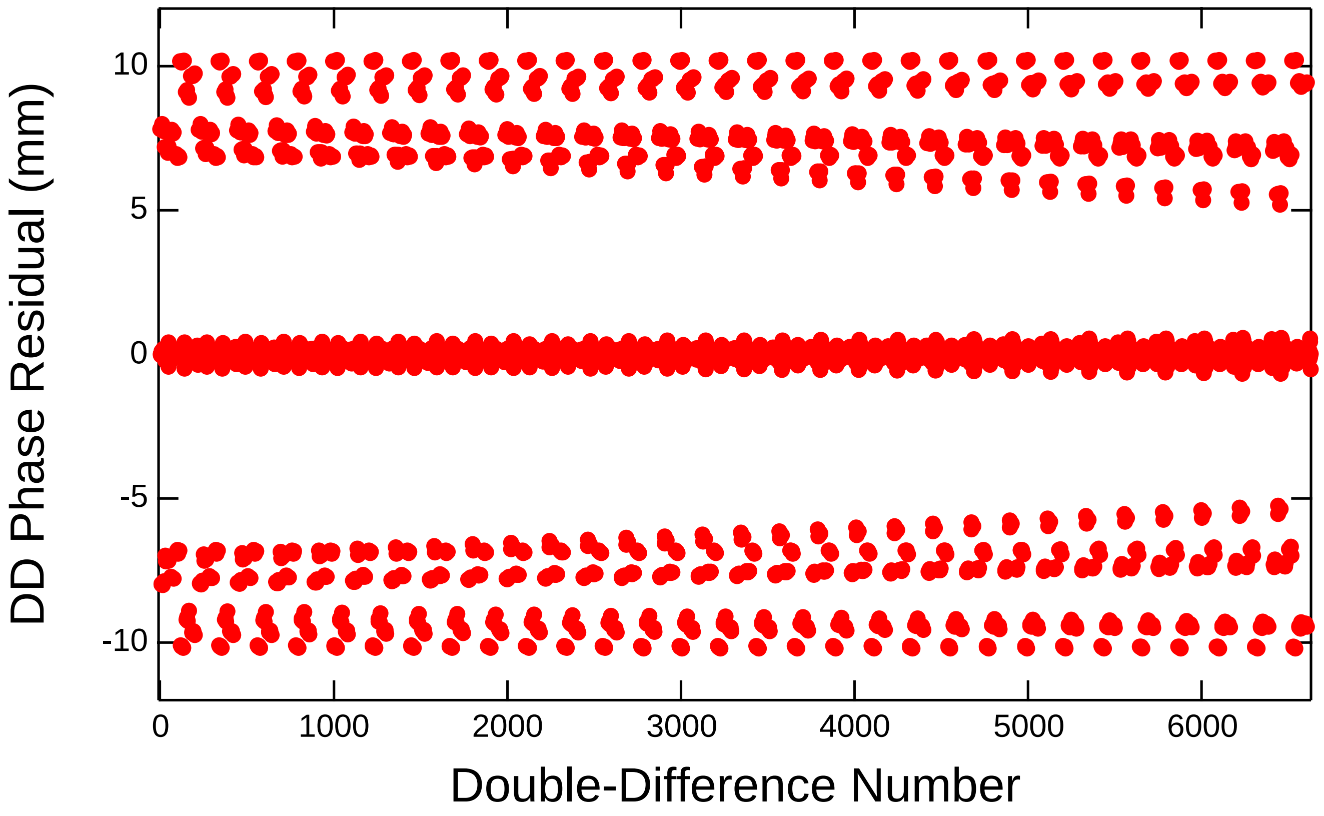
C



Least squares modeled the ±10 mm anisotropy as an adjustment to all atmospheric parameters of all sites. The anisotropy is mainly absorbed by the zenith delay parameter of all seven local sites, which are 3–4 mm. The parameters of all other sites are affected up to the mm level. Although the size of the formal uncertainties are smaller by a factor proportional to the (square root of) the number of observations, they are all inaccurate.

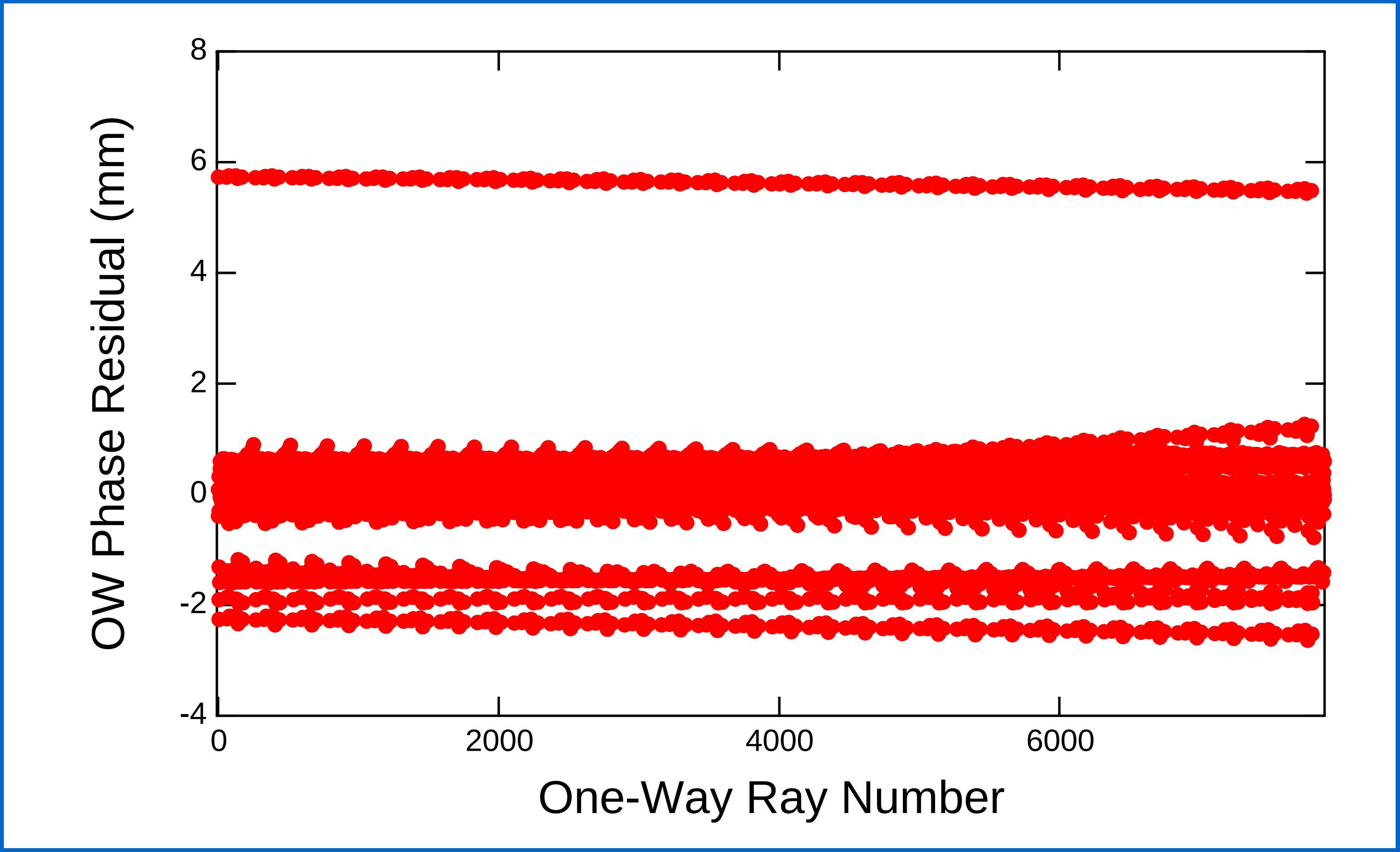
Calculate Double-Difference Residuals

C



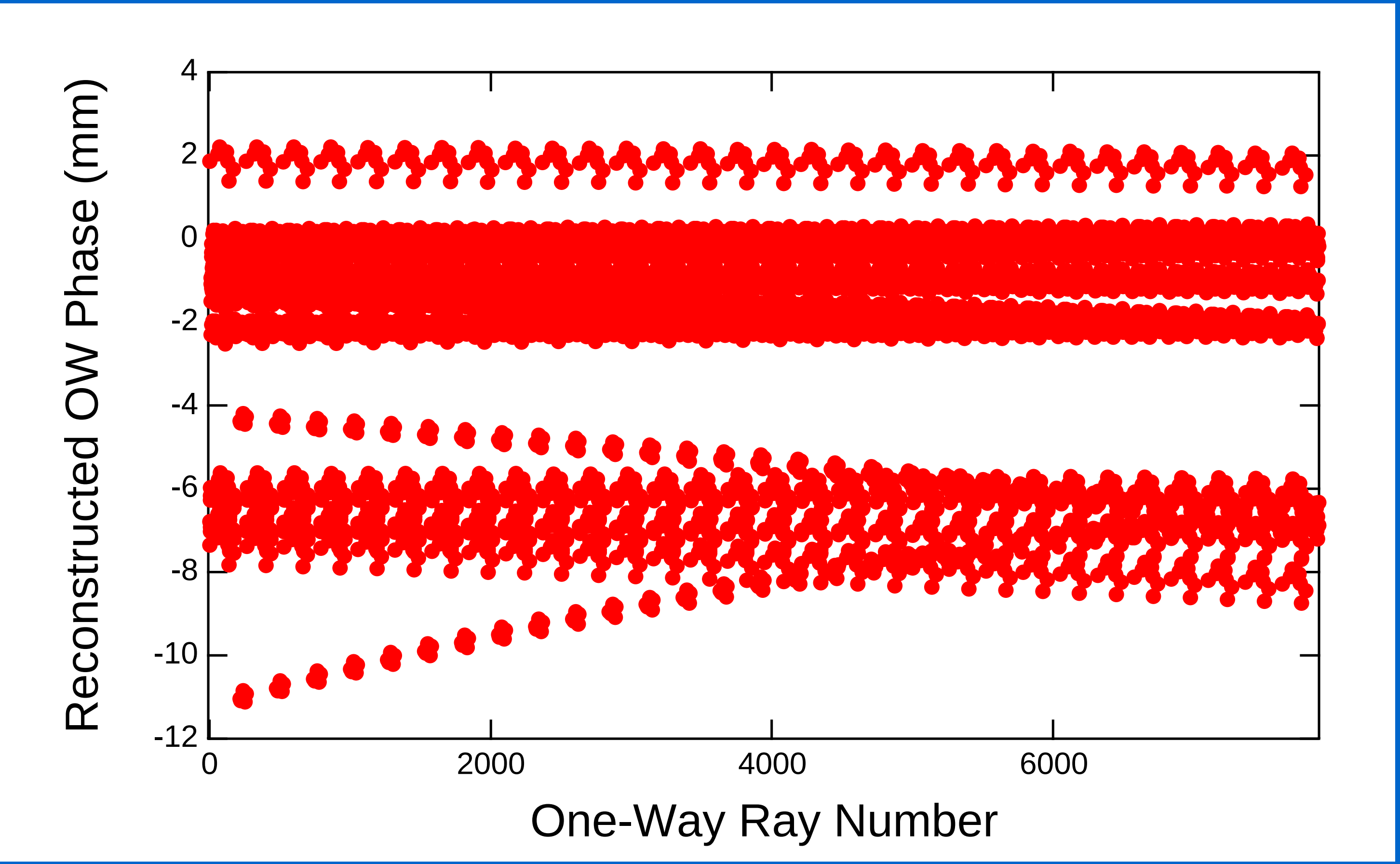
Unwrap Double-Difference Residuals

C



Reconstruct Atmosphere

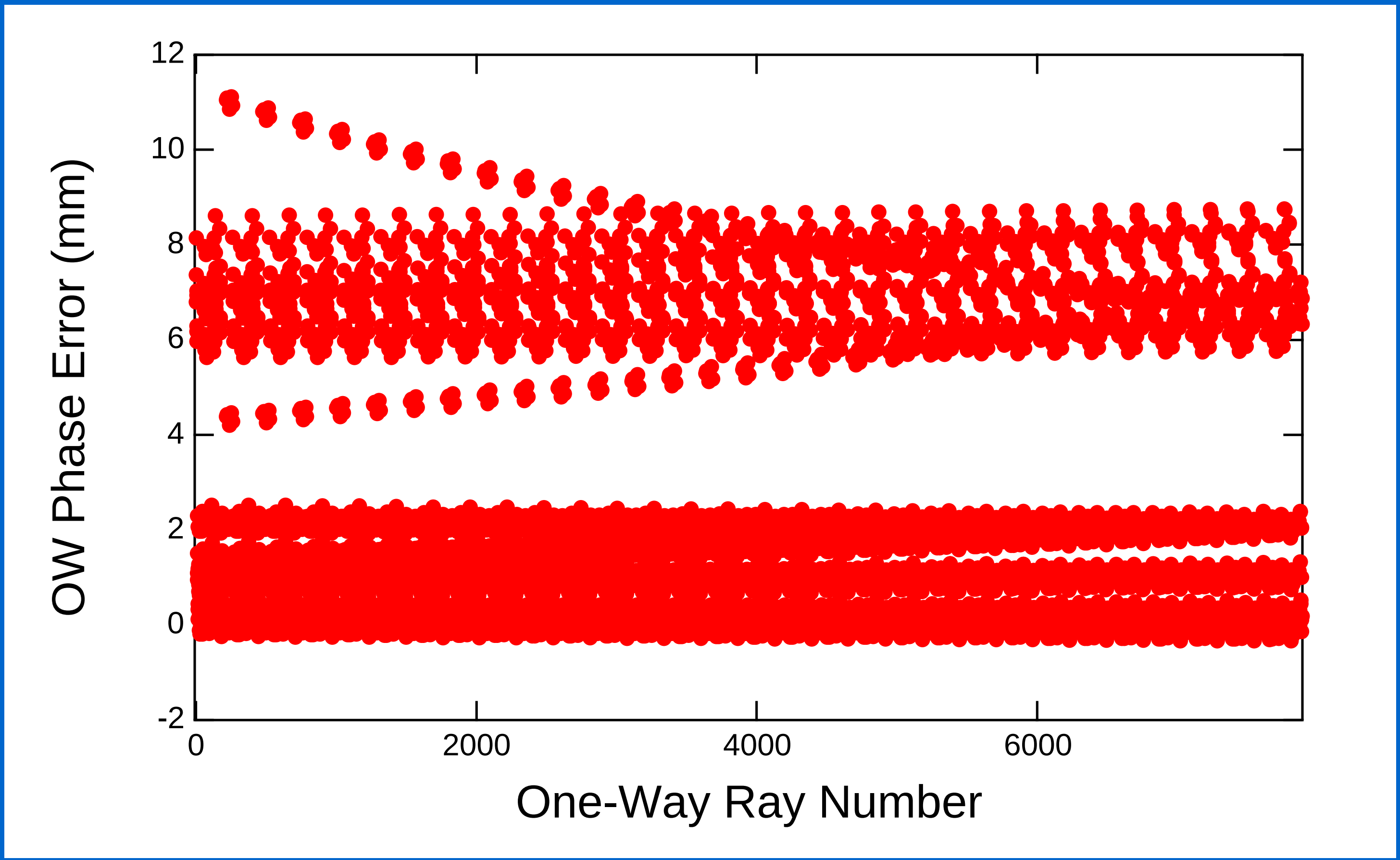
C



All seven regional sites recover ~9 mm of the 10 mm difference between the anisotropy ray and the rest of rays, but all its reconstructed phases are biased. The reconstructed phases of all other sites are also biased up to the 3 mm level, except for the distant sites, which for the low elevation-angle satellites, show biases at the 4–6 and 7–11 mm level.

Compare Simulated and Reconstructed Atmospheres

C



All reconstructed one-way phases at the sites that observed the 10 mm common anisotropy are in error by ~5–9 mm. Errors introduced by the double-difference algorithm are larger than the 10 mm anisotropy that we are trying to detect.

Summary of Simulation C

C

- All reconstructed one-way observations are biased.
- Errors amount to ~6–9 mm of phase for all one-way observations at all seven sites that observed the single 10 mm common anisotropy.
- Errors amount up to ~3 mm of phase at all sites that do not observe the anisotropy but are within <~1000 km of site ARM1.
- Errors amount up to ~11 mm of phase at the far distant sites, larger than the 10 mm common anisotropy signal that we are trying to detect.
- Errors remain significant through the duration of the entire simulation.

Conclusions

- All reconstructed slant wet delays using the standard method result in significant errors.

- The errors introduced by the standard method are commensurate with the magnitude of the anisotropy signal that we are trying to measure.

- Given these errors, the small improvement in the RMS error of reconstructed slant wet delays using the standard method is not a valid measure of algorithm performance.

- The accuracy of the standard method would be improved if external constraints on atmospheric parameters were available.