

# Long-term Performance of the VLT UT Active Optics System

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## ABSTRACT

For large telescopes, like the Very Large Telescope (VLT) unit telescopes, it is compulsory to use an effective and reliable Active Optics system in order to guarantee the optimal optical performance. The active optics ensures that the actual wavefront aberrations introduced by the telescope itself are kept as low as possible. In order to evaluate the long-term performance of this system, an extended timeseries data analysis for all four unit telescopes (UT) was performed. The results presented in this paper demonstrate that the VLT UT active optics system works very stable and reliable with no significant performance degradation over time.

**Keywords:** VLT, active optics, timeseries analysis, optical quality

## 1. INTRODUCTION

### 1.1 Active Optics System of the VLT unit telescopes

For telescopes with large and thin solid meniscus mirrors, like the Very Large Telescopes (VLT) unit telescopes (UT), it is compulsory to use an effective and reliable active optics system in order to guarantee the optimal optical performance [1]. The actual performance of a telescope depends strongly on the avoidance of wavefront aberrations. The main error sources, ordered according to the average frequency of their band-pass, are optical design and manufacturing, structural deformations, support errors, local air and the free atmosphere. By definition, active optics corrects only slowly varying errors generated by the telescope itself and, partially, by air effects near the telescope. The frequency limit for the active optics system is 0.03 Hz. Systems that deal with higher frequency aberrations are called adaptive optics systems and are not considered in this paper.

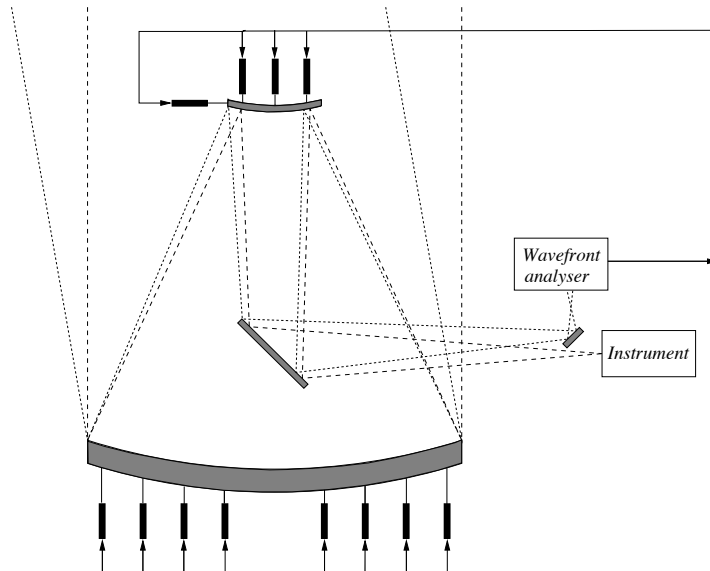


Figure 1. Basic scheme of the UT Active Optics system

The VLT active optics system runs in closed loop operation, using a Shack-Hartmann sensor for wavefront analysis and performing the corrections on the primary and secondary mirrors. Movements of the secondary mirror correct defocus and decentering coma, while all other wavefront errors are corrected by changing the shape of the primary mirror. The latter consists of 150 computer controlled axial actuators, applying a distribution of forces at the back of the mirror. Periodically the image analyzer calculates the deviation of the image from the best quality. The image analysis typically requires about 30 seconds in order to integrate out the effect of atmospheric seeing. The computer decomposes the deviation into single optical contributions and calculates the force correction, which each active element has to perform to achieve the optimal optical quality. The set of 150 correction forces, one for each axial actuator, is computed and transmitted to the local control of the M1 Cell (-M3 Tower) for execution. The basic setup of the UT Active Optics System is shown in figure 1.

The active optics system of the VLT is now continuously in operation since 1998. A first indicator for the reliable operation is the very low number of problem reporting tickets issued for this subsystem. In the 15 years of operation, no mayor intervention was necessary. For more details on the UT Active Optics system refer to [2], for a first performance estimate after first-light to [3] and for more analysis and improvements to [4].

## **1.2 Detail on Timeseries Analysis**

In order to evaluate the long-term performance of the system, an extended timeseries data analysis of the available telemetry data for all unit telescopes was performed. The dependence of the system performance on external (e.g. seeing, wind speed and ambient temperature) and internal parameters (e.g. performance of Shack-Hartmann wavefront analyzer, the used algorithms for wavefront reconstruction and telescope altitude position) is analyzed in order to give a detailed performance estimate for the different unit telescopes. To assess the basic performance of the system, the residual RMS wavefront error is used as performance indicator. The RMS error is the expected error after application of the forces that correct the last fitting. Assuming the force application to be perfect then this corresponds directly to the optical performance of the system. Furthermore, the D80 value was analyzed. It is the diameter of the 80% enclosed energy calculated by the Active Optics system based on the residual aberrations after correction. These two parameters allow assessing the global performance of the system and to estimate the optical quality of the corresponding telescope.

For the analysis itself, telemetry data from the ESO archive was used. As data is only available for the last ten years, it was not possible to assess the performance since first-light for all four telescopes. For UT1 and UT2, data from 2006 on is available. For UT3 and UT4, local copies of the log files were available so that here the performance since first-light can be reconstructed and therefore UT3 and UT4 are used to show the dependence of the performance on external and internal parameters. As all four telescopes behave very similar (checked with data from recent years) so that the behavior of these two UT's is also valid for the other two telescopes.

## **2. GLOBAL LONG TERM TELESCOPE PERFORMANCE**

### **2.1 Statistics for the Residual Wavefront Error and D80 Value**

In figure 2 the histograms of the residual wavefront error (res RMS) and the D80 value for all four telescopes and the whole periods with available data are shown. As can be seen, the distribution for the D80 value is very similar for all four telescopes with a peak around 0.18 arcsec, which indicates that the performance is very stable without any large fluctuations or changes over time. In contrast to that, there are differences in the residual RMS values. The main peak for all telescopes is around 80 nm while UT2 and UT3 show a second peak at around 130 nm and for UT1 the falling tail is significantly broadened. The changes in the distributions of the residual RMS result from two different algorithms that are used for wavefront reconstruction and not from a performance degradation. This will be discussed in more detail in chapter 3 of this paper.

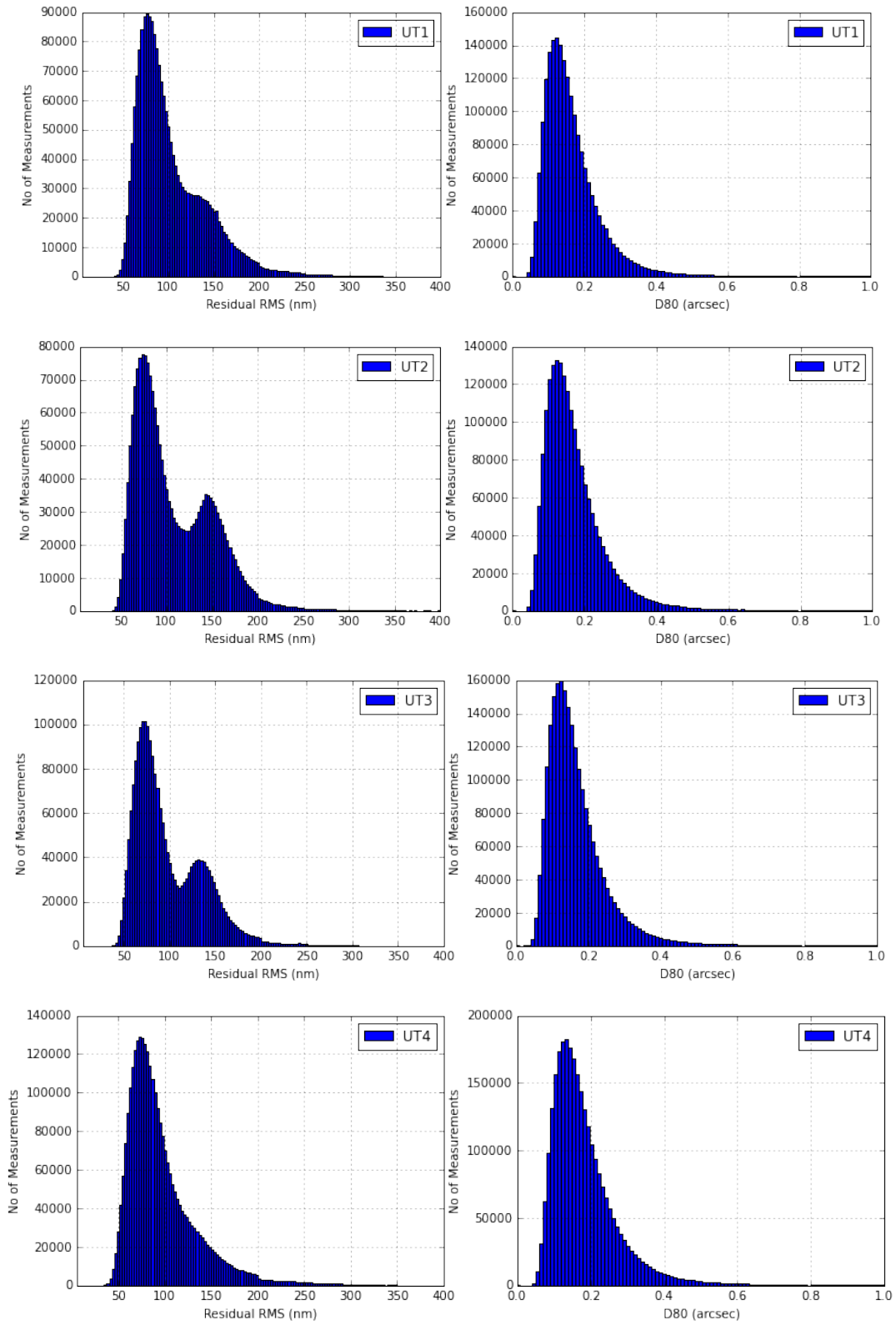


Figure 2. Histograms for the residual wavefront RMS and D80 value for all four UT's

## 2.2 Temporal Evolution of the Residual Wavefront Error and D80 Value

In order to show the temporal evolution of the residual RMS and the D80 value, the weekly averages of both parameters as a function of time are plotted in figure 3 (residual RMS) and figure 4 (D80 value).

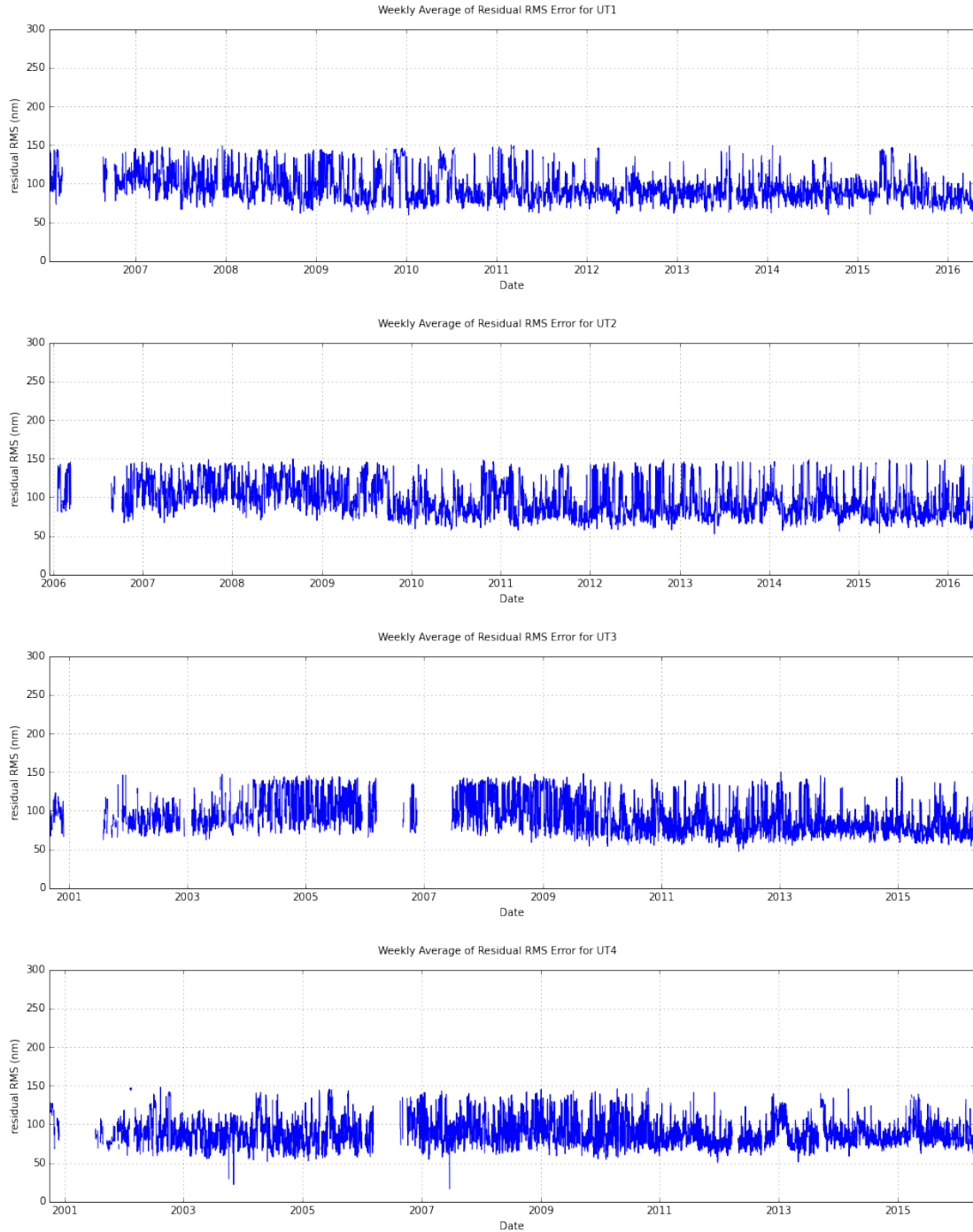


Figure 3. Weekly average of the residual RMS as a function of time.

In figure 3 can be seen, that also the evolution of the residual RMS over time is stable. The visible peaks in certain weeks result (with the exception of UT4 in the years 2005 till 2011, see chapter 3) from the switch to a more stable but less

accurate algorithm for wavefront reconstruction. The gaps that can be seen in the plots for the years 2001 (all telescopes), 2006 (UT3 & UT4) and 2007 (UT3) are because of corrupted log files so that no data was available.

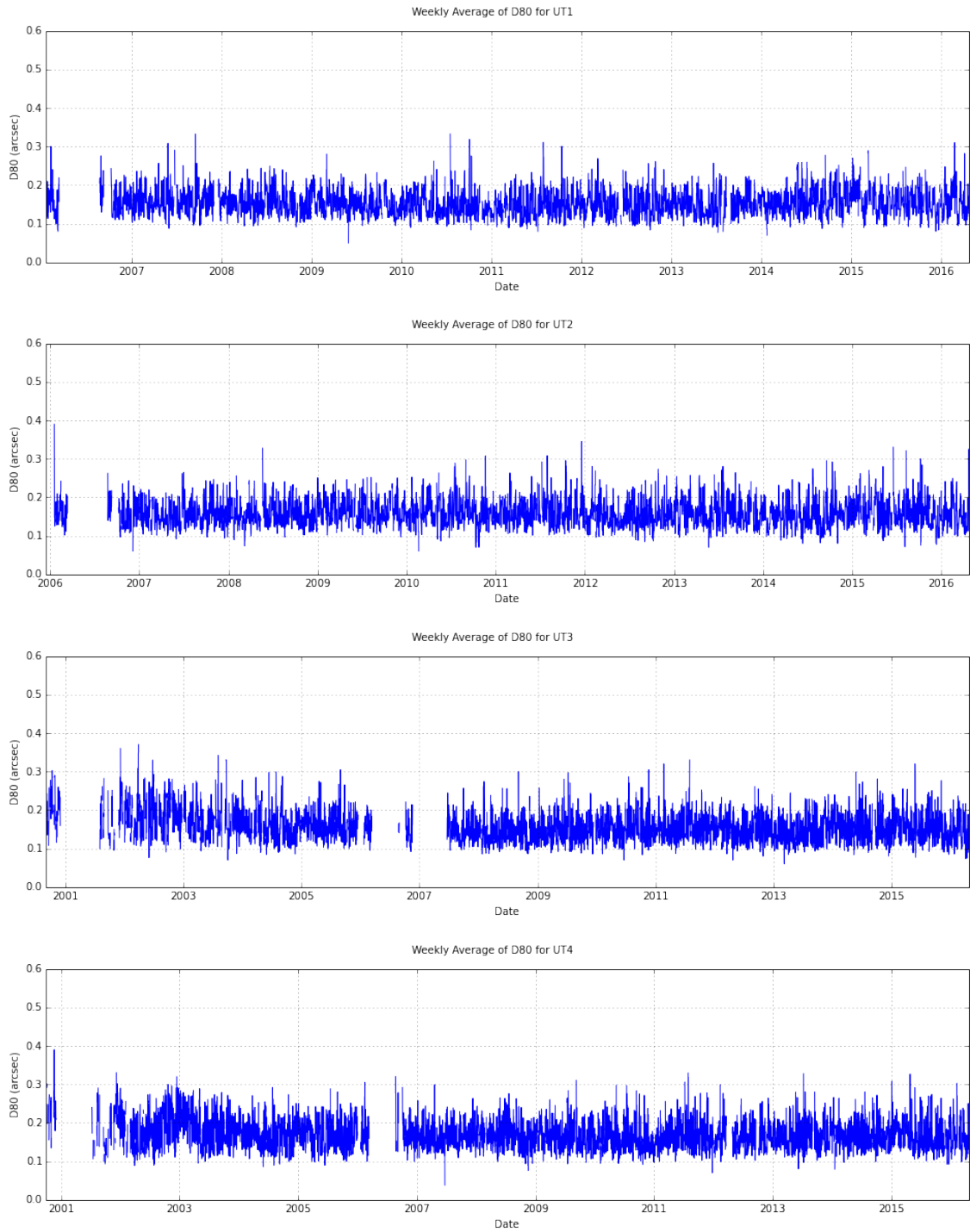


Figure 4. Weekly average of the D80 value as a function of time.

In figure 4 can be seen, that also the evolution of the D80 over time is stable and no degradation occurs. The mean value for all four telescopes is around 0.18 arcsec.

### 3. DETAILED PERFORMANCE OVERVIEW FOR A UNIT TELESCOPE

#### 3.1 Percentage of Successful Performed Corrections

The active optic system applies in standard operations (can be changed by the operator when conditions make it necessary) corrections only if the measured residual RMS is smaller than 200 nm. In order to check the performance of the system, the percentage of image analyses and active corrections with values larger than 200 nm was calculated on a yearly basis. In the left graph of figure 5 can be seen that for UT3 the calculated residual RMS is around 6% over the lifetime of the telescope. Between 1% and 3% of the applied corrections are above 200 nm, which means that in this cases the operator increased the limit manually in order to allow operations under adverse conditions. UT1 and UT2 show very similar performance and the number of performed image analysis with a residual wavefront error larger than 200 nm are also in the range of 6%.

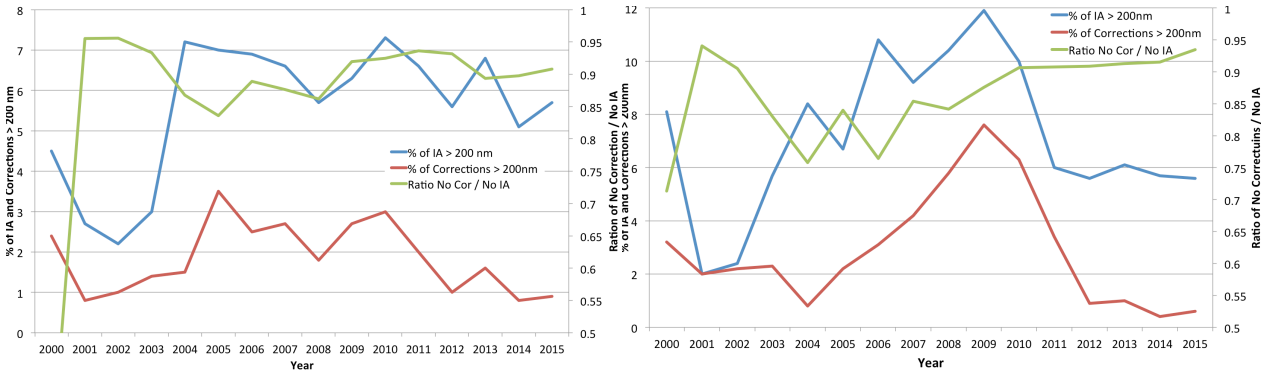


Figure 5. Percentage of image analyses and active optics corrections larger than 200 nm for UT3 (left) and UT4 from 2000 till 2015 (blue: % of IA > 200 nm, red: % of applied corrections > 200nm, green: ratio between IA and applied corrections).

Different is the behavior of UT4 (right plot of figure 5); there a large increase of the residual RMS (both for image analysis and applied corrections) between 2005 and 2011 can be observed. As can be seen later on in section 3.3, this degradation occurs only in the Nasmyth A and Coudé focal positions.

#### 3.2 Influence of Wavefront Reconstruction Algorithm

For the reconstruction of the wavefront, two different algorithms can be used. While “Wave” provides a much better performance, “Slope” is more robust and allows for example operation when part of the Shack-Hartman imagine is vignetted. In figure 6, the histograms for residual RMS and the D80 value for both algorithms are plotted. As can be seen, the peak for the “Slope” algorithm is shifted by about 50 nm to higher residual RMS values whereas the peak for the D80 value is not shifted. This means that the more robust “Slope” wavefront reconstruction algorithm does not influence the quality of the D80 value but only the residual wavefront error. During the lifetime of UT3, 9% of all active image analyses were performed with the “Slope” algorithm.

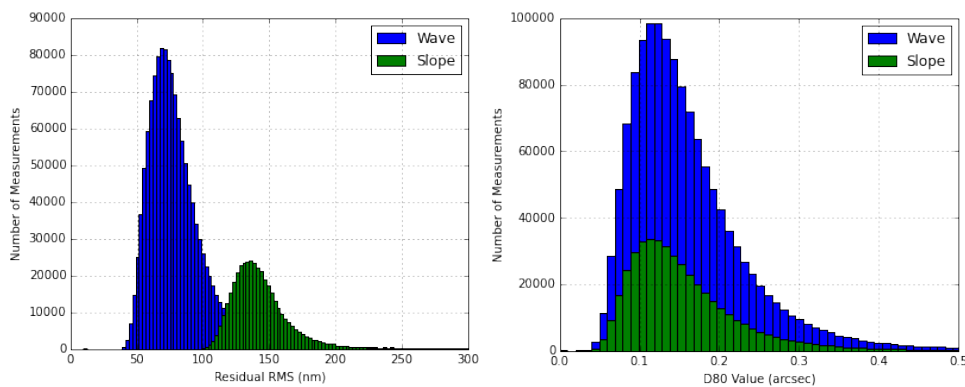


Figure 6. Histograms of residual RMS (left) and D80 value (right) for two different algorithms (blue: wave, green: slope) for wavefront reconstruction for UT3

### 3.3 Performance of Different Focal Positions

So far, only the global performance of the UT was investigated but the VLT UT can be operated with 4 different focal points, Nasmyth A and B, Cassegrain and Coudé. In figure 7 the histograms for these four different focal positions for UT3 and UT4 are displayed.

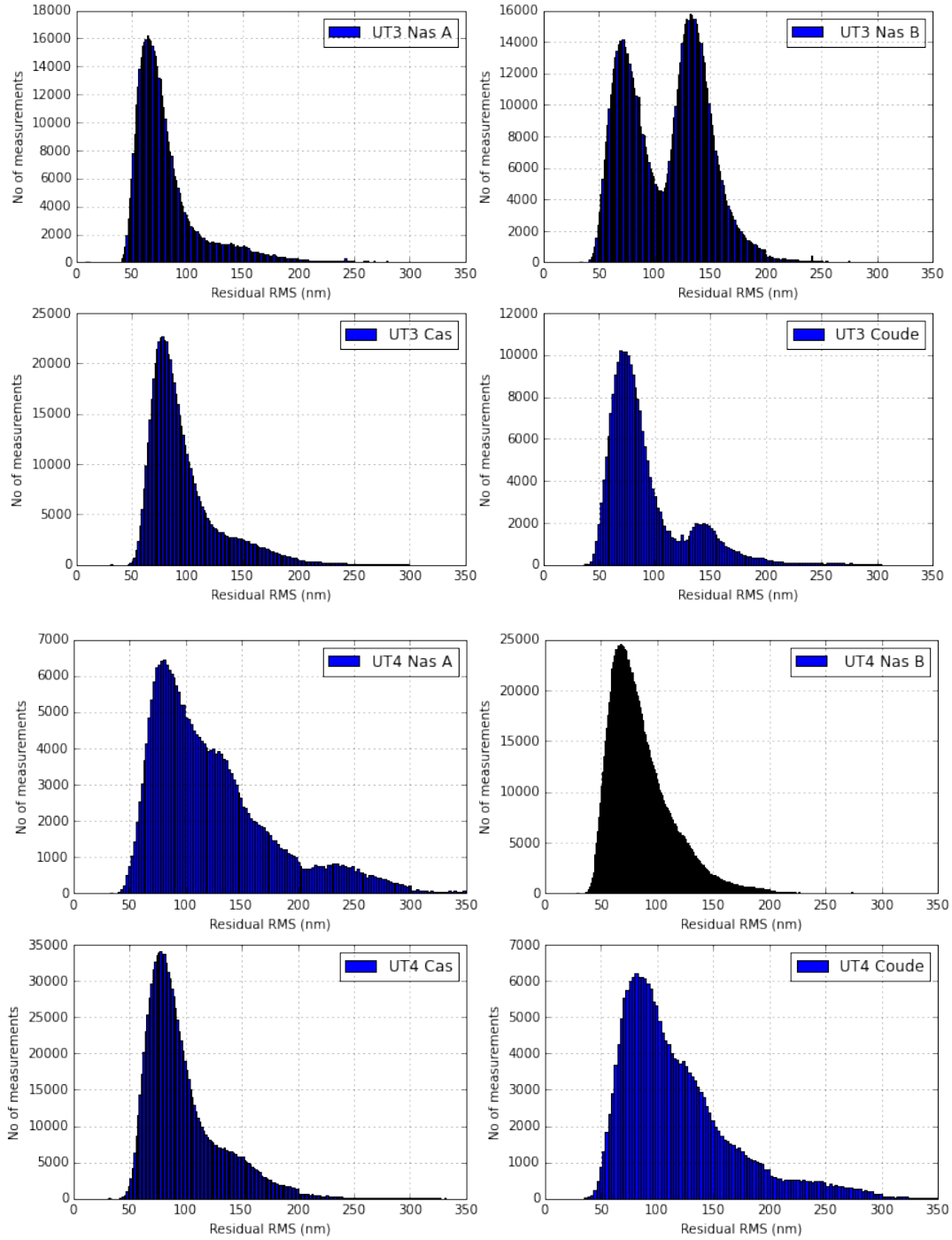


Figure 7. Histograms of residual RMS for UT3 (upper 4 graphs) and UT4 (lower 4 graphs) for the different focal positions (from top left to bottom right: Nas A, Nas B, Cassegrain, Coudé)

In figure 7, it can be seen that for the Nasmyth A and Coudé focus positions of UT4 a degraded performance can be observed. Figure 8 shows that this degradation occurs in the years 2006 till 2011 and when the “Wave” algorithm is used.

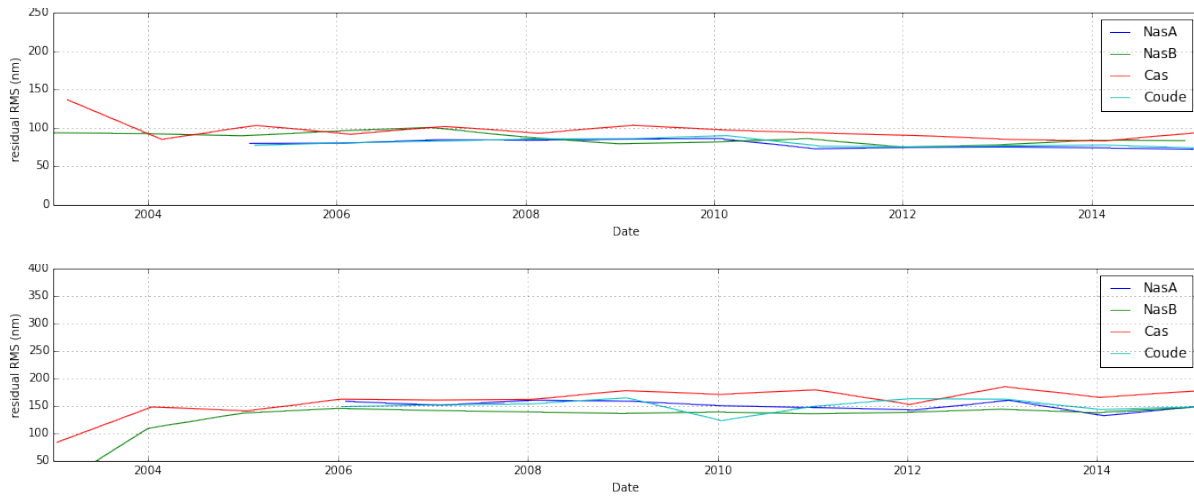


Figure 8. Yearly averages of the residual wavefront error for “Wave” (top) and “Slope” (bottom) wavefront reconstruction algorithm for the four different focal positions of UT3

The plots in figure 8 show that the performance for both wavefront algorithms is constant over time for all four focal positions of UT3. The mean residual wavefront error is 80 nm for the “Wave” algorithm, which is considered as the nominal algorithm for optimal performance.



Figure 9. Yearly averages of the residual wavefront error for ‘Wave’ (top) and ‘Slope’ (bottom) wavefront reconstruction algorithm for the four different focal positions of UT4

As can be seen in the upper plot of figure 9, the residual RMS for Nasmyth A and Coudé are significantly increased till 2011 (for these focal positions, no data before 2006 was available). In this period, only 19% of all observations were performed in Nasmyth A and Coude focus. Searching the Paranal Problem reporting system did not lead to a clear indicator what was the reason for that increase. The most likely cause was a software problem with the technical CCD that is used for the Shack-Hartmann Analyzer, which was solved in 2011 by a software update. An analysis of the Shack-Hartmann parameters on the Star-Reference pair count backs that assumption as for Nasmyth A and Coudé (both use the same Shack-Hartmann Analyzer) the mean count was below while it was for the other two focus positions 400.



### 3.4 Shack-Hartmann Analyzer Performance

One difference that can be seen over the years is the count of the 5<sup>th</sup> brightest pixel in the Shack-Hartmann analyzer. Shortly after commissioning, the automatic exposure time facility was added to the active optics system, which aims to keep the 5th maximum pixel above 800 counts and away from the 4096 counts of saturation. It can be seen in the left plot of figure 10 that in the year 2003 the upper bound is well kept while there are still some image analyses where the count is below 800. In contrast to that, in the year 2015 the count goes up to 60.000 and the lower limit is around 2000 counts. This change is due a change to a new generation technical CCD (16 bits ADU in contrast to 12 bits of the old).

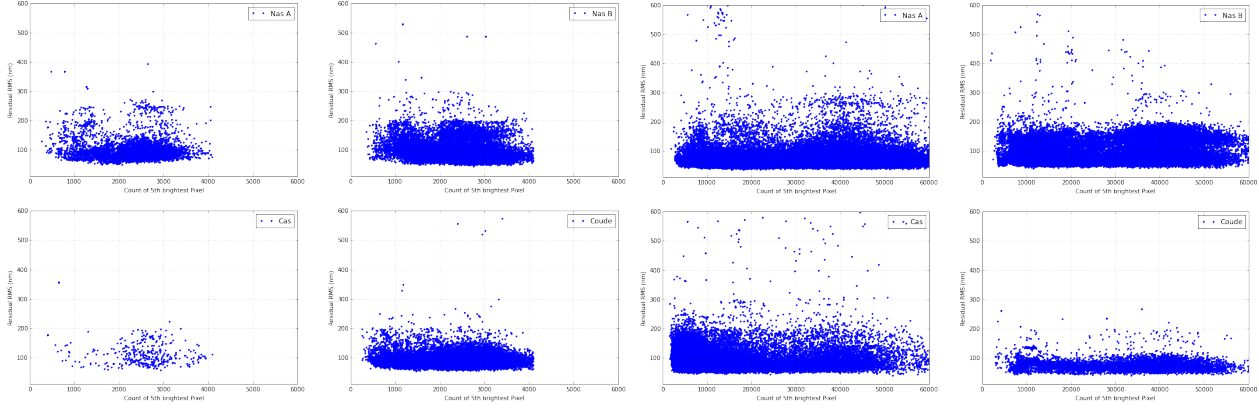


Figure 10. Count of the 5<sup>th</sup> brightest pixel for UT4 for the years 2003 (4 left plots) and 2015 (4 right plots) for all four focus positions (from top left to bottom right: Nas A, Nas B, Cassegrain, Coude)

An analysis of the performance dependence showed that there is no direct relationship between the upper limit of the count for the 5<sup>th</sup> brightest pixel and the residual RMS and the D80 value. The increase led to a higher number of star-reference pairs but also increased the background count. In contrast to that, a performance degradation of about 20% for counts below 800 was observed. Looking at the statistics of the star-reference pair count, optimal performance is established when the star-reference pair count is between 350 and 500. For a pair count of 300, the performance decreases by 20%.

## 4. PERFORMANCE COMPARISON FOR TWO DIFFERENT PERIODS OF TIME

In order to compare the actual performance of the system with the performance after commissioning, two different periods (first: 2000 – 2003 and second: 2012 – 2015) were analyzed. The analysis was done with multiple years in order to obtain a better statistics for the measured values.

### 4.1 Relationship Between Residual RMS and D80 Value

In figure 11, the D80 value is plotted as a function of the residual wavefront error. As can be seen, there is a linear increase in the range of 40 nm to 120 nm, which is also the nominal working range (about 90% of all corrections are performed in that range, assuming that the nominal “wave” algorithm for wavefront reconstruction is used). Furthermore, there is almost no difference between the two periods.

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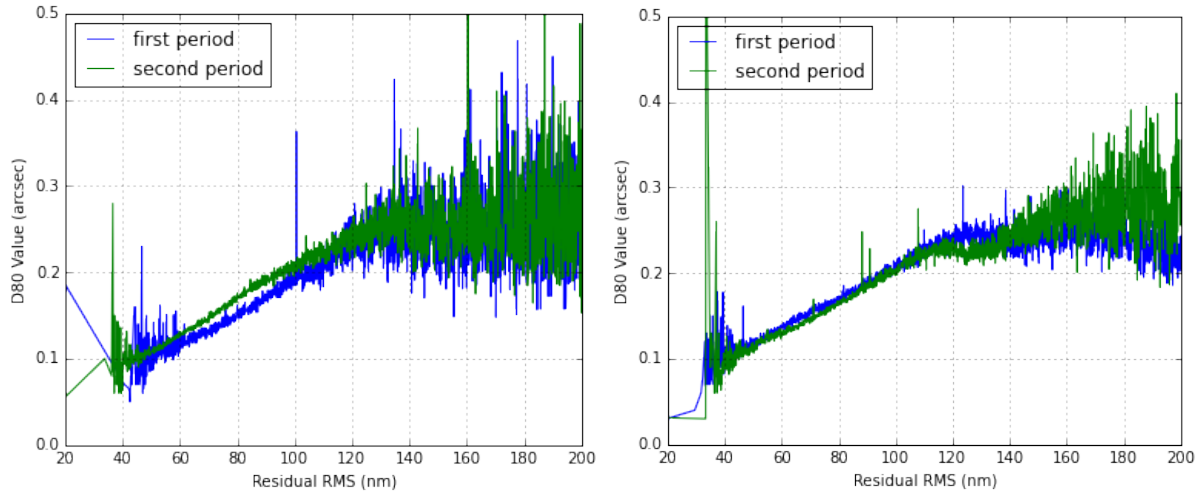


Figure 11. D80 value as function of the residual RMS for UT3 (left plot) and UT4 (right plot) for two different periods (blue: 2000 - 2003 and green: 2013 - 2015)

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#### 4.2 Dependence on Measured Aberrations

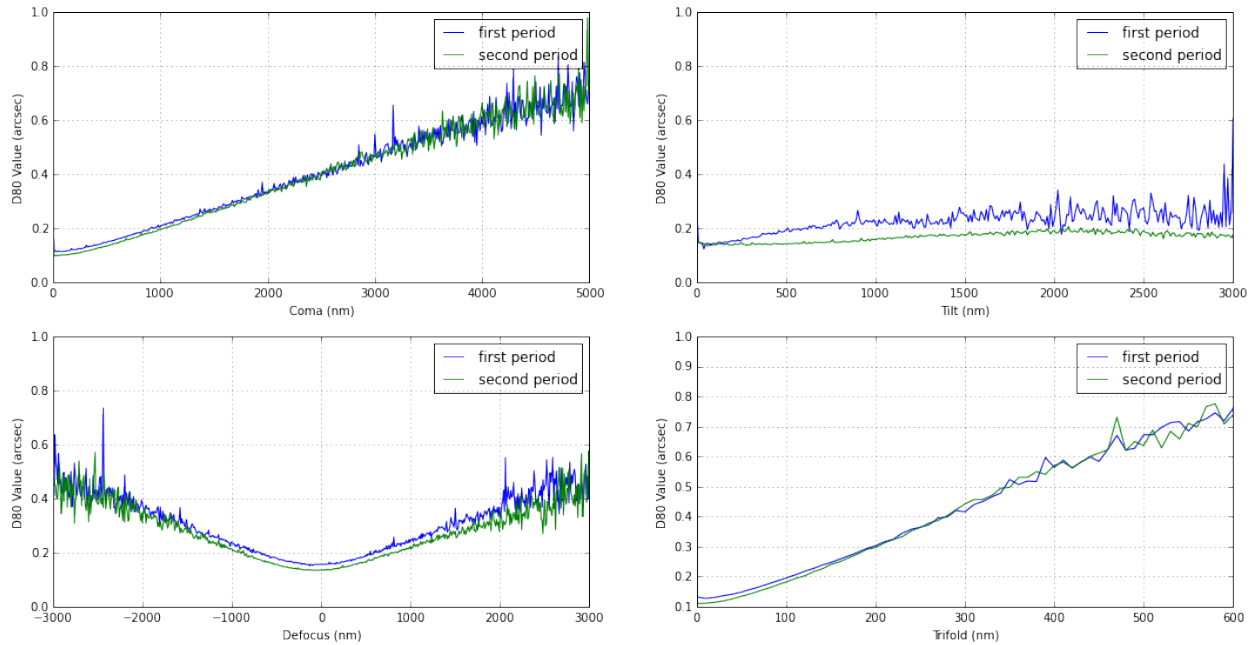


Figure 12. D80 value of UT3 as a function of four different aberrations: Coma (top left), Tilt (top right), Defocus (bottom left) and Trifold (bottom right) for two different periods (blue: 2000 – 2004 and green: 2012 – 2015)

In order to show the influence of the measured optical aberrations on the optical quality in figure 12 the D80 value is plotted as function of four different aberrations.

### 4.3 Dependence on Altitude Position

Figure 13 shows the dependence of the D80 value on the altitude position of the telescope. It can be seen that in the range between 45 and 85 degree (zenith at 90 degree) then performance is almost independent on the actual altitude position. Only for very low angles, where the effect of Gravity on the thin (17 cm with a diameter of 8.2 m) main mirror becomes more dominant, slight performance degradation becomes visible.

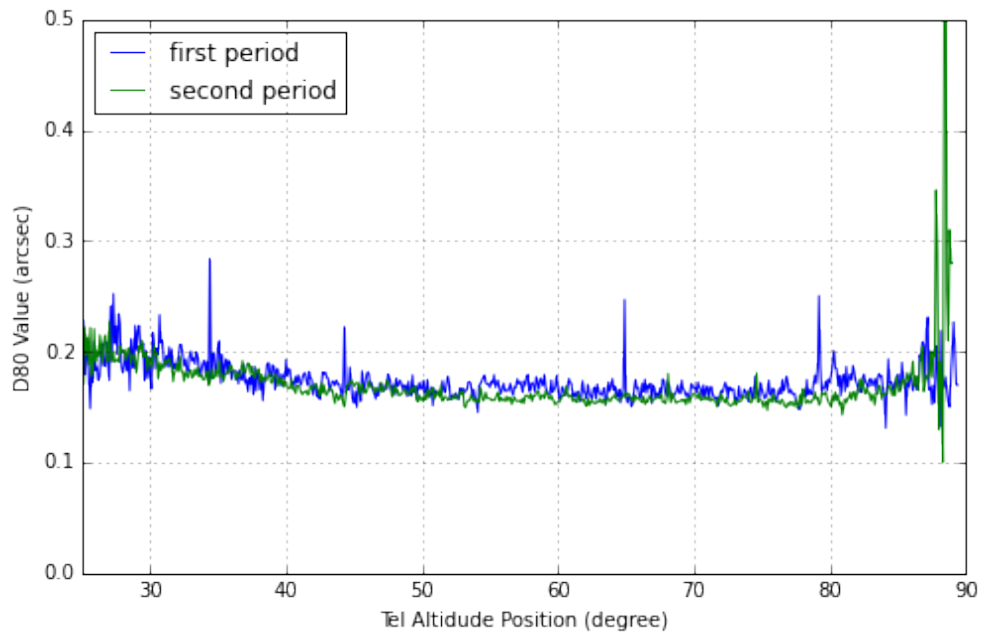


Figure 13. D80 value of UT3 as a function of the telescope altitude position for two different periods (blue: 2000 – 2004 and green: 2012 – 2015)

### 4.4 Dependence on Environmental Parameters

In this section, the performance in dependence on environmental parameters is analyzed. In figure 14 the D80 value is plotted as function of the seeing. As can be seen, there is a linear dependence in the nominal seeing range from 0.5 to 1.5. This has previously been observed [4]. The behavior in both time periods is similar so that

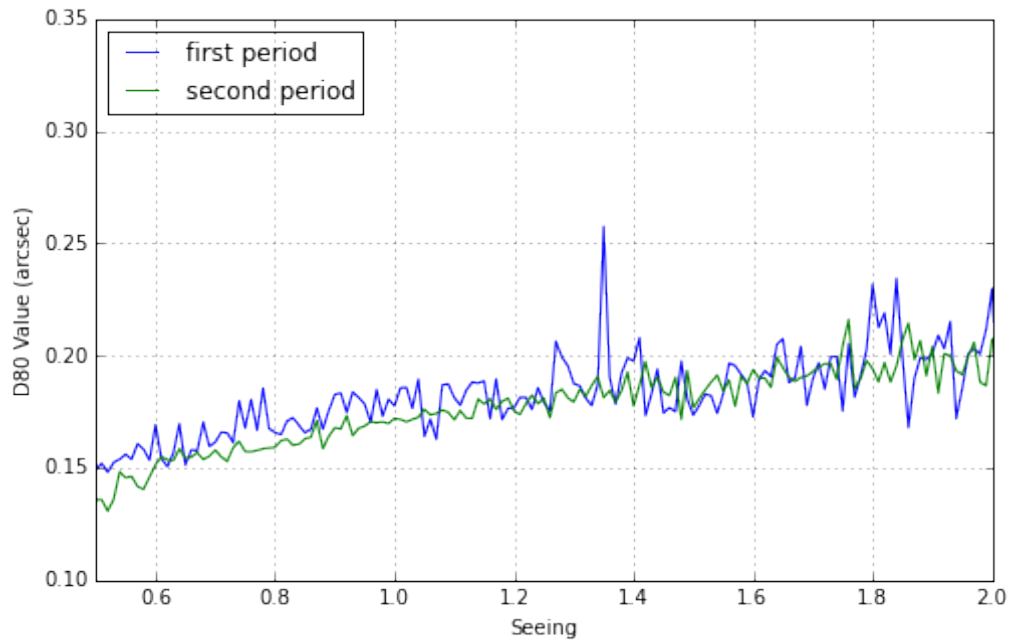


Figure 14. D80 value as a function of the seeing for two different periods (blue: 2000 – 2004 and green: 2012 – 2015)

In figure 15, the dependence of the D80 value on the wind speed is plotted. It can be seen that the performance between 5 m/s and 12 m/s is almost independent on the wind speed. The performance decrease below 5 m/s occurs most likely from the local seeing in the dome, which cannot be eliminated by averaging. The limit for UT operation is 18 m/s.

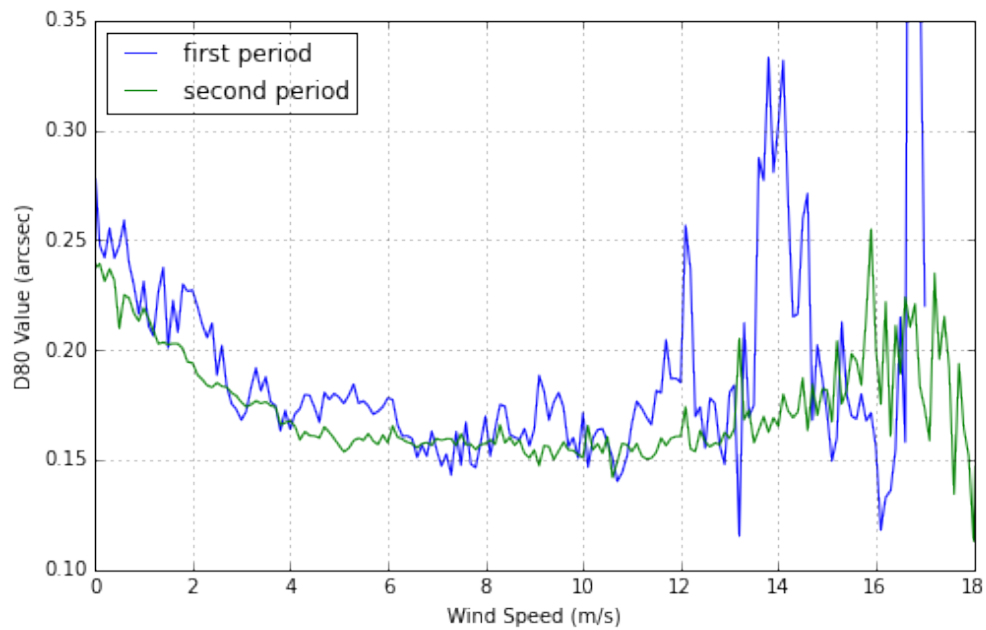


Figure 15. D80 value as a function of the wind speed for two different periods (blue: 2000 – 2004 and green: 2012 – 2015)

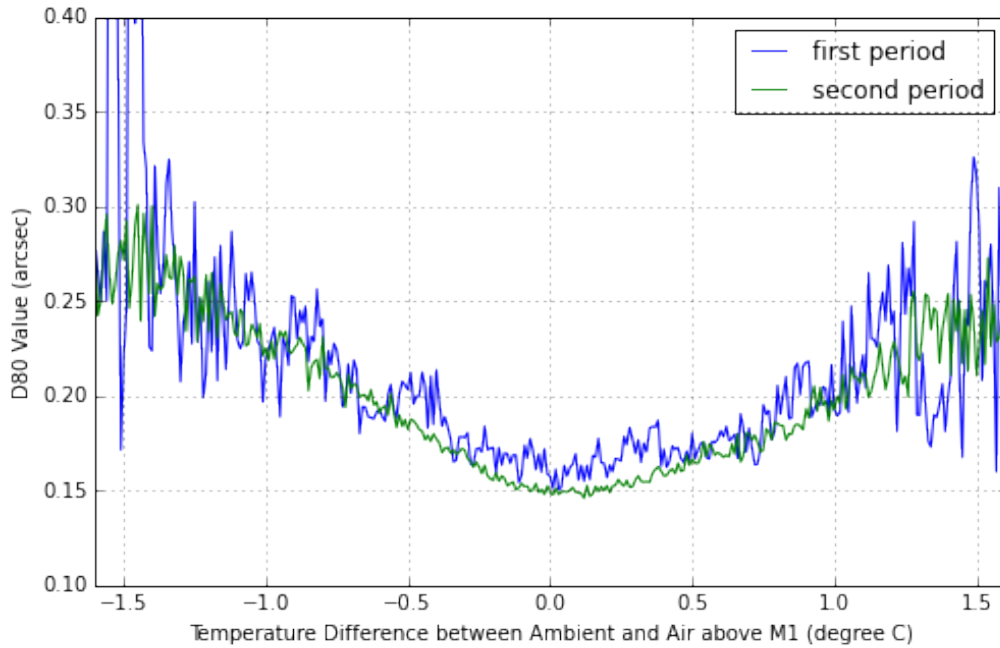


Figure 16. D80 value as a function of the temperature difference between ambient and the air above the main mirror for two different periods (blue: 2000 – 2004 and green: 2012 – 2015)

The last environmental parameter that was investigated was the dependence of the D80 value on the temperature difference between ambient temperature and the air temperature above the main mirror. As can be seen in figure 16, the optimal performance is given when the temperature difference is zero. For a temperature difference of  $\pm 1$  degree, the performance is about 10% lower. 90% of all active corrections are within the range of  $\pm 1$  degree. Again, for both periods the behavior is similar with no degradation visible.

The results of section 4 demonstrate that the active optics system of the VLT unit telescopes works within the nominal operation conditions with almost no dependence on telescope altitude position and environmental conditions. Furthermore, the plots show that there is hardly any difference between the two periods so that it can be assumed that the actual performance is close to the one after commissioning.

## 5. CONCLUSION

The performed timeseries analysis demonstrated that the active optics system of the VLT unit telescopes works stable and reliable. The comparison of two different time periods (the first four years after first light and the last four years of operation) showed that the behavior of the telescopes did not change which means that no degradation over time is visible. The dependence of the performance on optical aberrations, telescope altitude position and environmental parameters is as expected and do not show any anomaly. A further indicator for the reliable operation is the very low number of problem reporting tickets issued for this subsystem. In the 15 years of operation, no mayor intervention or upgrade was necessary. A bit surprising was that the increase in the residual wavefront error for UT4 Nasmyth A and Coudé focus in the years 2006 till 2011 was not reported and no clear solution identified in the ticketing system. In these two focal positions (19% of UT4 observations were performed in these focal positions), the telescope operated for several years with an increased residual wavefront error till it came back to normal performance.

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