SkyWave
Dealing with Seeing

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1. **Introduction**
The goal of this document is to discuss the effects of the Earth's atmospheric turbulences, known as seeing, on the measurements made by SkyWave (SKW) and the related impact on the quality of the telescope alignment.
More specifically, what are the conditions, for a given telescope optics and seeing, to keep the inevitable seeing effect at an acceptable level such that image to image fluctuations have minimum impact on the telescope alignment task when using SKW.

2. **Setting expectations**
In the field of imaging optics, from a practical standpoint, we usually consider a system to be diffraction limited (DL) when its Strehl's ratio (SR) is at, or above, 0.8, or 80%. The SR value is a simple way to summarize the optical performance in one number, but it makes sense only if this number is high enough, typically above 50%. Low SR values leads to speckle types of point spread functions (PSF) with spread energy and several peaks. We should always remember that when doing astro-imaging each and every star in the FOV translates into your telescope PSF. Having said that we should also understand that only few scopes, mainly those of small apertures (few inches at most), are DL indeed in this context. The reason being seeing effects. For most us are seeing limited before we could be DL. It suffices to remember that the angular DL of a telescope (the FWHM Airy disk central peak), in arc-second (arc-s), is given by the ratio of the wavelength λ of the considered light over the telescope aperture diameter (D). We usually set the wavelength value mid-range through the visible spectrum, this would be 550nm.

$$DL_{FWHM} = 2.11 \cdot 10^5 \frac{\lambda}{D}$$

For a 4" telescope (D), or about D=100mm, we have @ 550nm:

$$DL_{in\ arc-s} = 2.11 \cdot 10^5 \frac{550 \cdot 10^{-9}}{0.1} = 1.16\ arc - s$$

Which is already smaller than most seeing values at most locations.

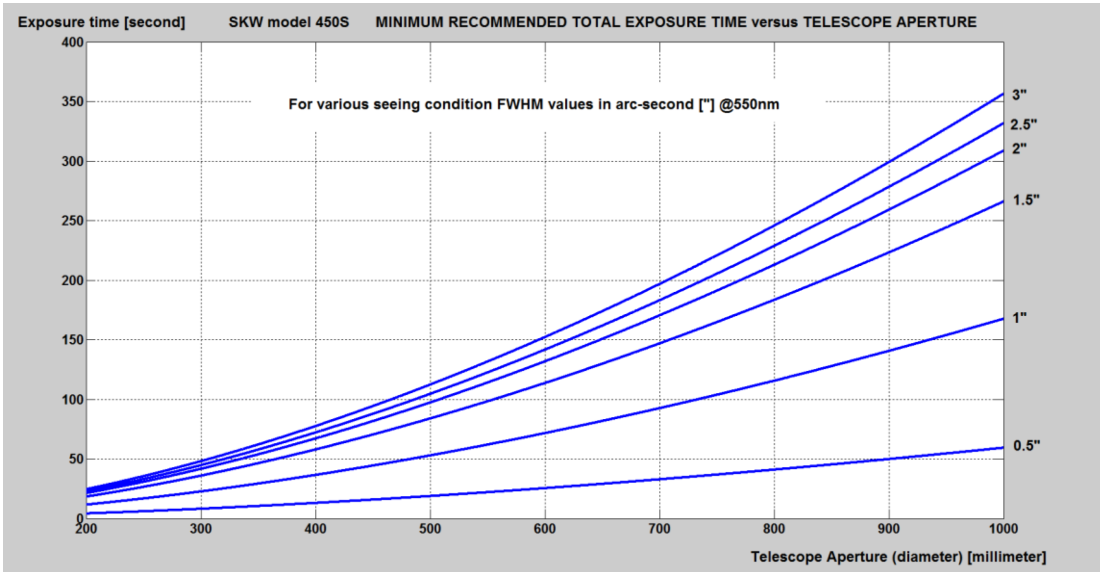
SKW is a true wavefront (WF) sensor solution just like any other wavefront sensor such as a Shack-Hartmann for instance, however it a software based approach which does not require any WF sensor dedicated hardware, just your imaging camera and a mean to defocus.
Consequently SKW computes optical aberrations from the WF it captures, including the SR. However, using the SR value alone as a metric for telescope alignment would make sense only in seeing free situations, like on the lab using an optical bench, or on the space.
As we saw above as soon as the scope aperture (D) goes above few inches we are seeing limited, not DL anymore.
Of course we could use SKW, or any wavefront sensor for that matter, and align a telescope monitoring its SR with an actual star aiming for 80% or more.
However, there is a point of diminishing return in this process due to the seeing's blur size relative to the scope DL.
One can, and should, end the alignment process when the telescope PSF, with whatever aberration left, is smaller than the seeing blur, to some level.
Spending more time and energy doing better than that does not translate to any measurable improvement in the final image quality (like its MTF).

There is of course a notable exception, beside going into space, this is lucky-imaging, since in essence this technique works at the DL of the telescope keeping only frames for which the seeing is smaller than the scope's DL.
But for all the other applications we can set a "sweet" spot, or threshold, for the SR, or equivalent metric, during the telescope alignment process, relative to the seeing at which the telescope operates, such the final image quality remains seeing limited.
This is exactly what the SKW collimator tool's score provides. The SKW results reported in term of alignment scores are directly related to the local seeing set by the user in SKW, this also sets the SKW expectation. SKW uses the WF and related SR, among things, in conjunction with the seeing for computing this score such as the final image quality is seeing limited, left over telescope aberrations, f any, are then negligible.
For that reason we recommend aligning the telescope when the seeing is at its average/operational local value or better.

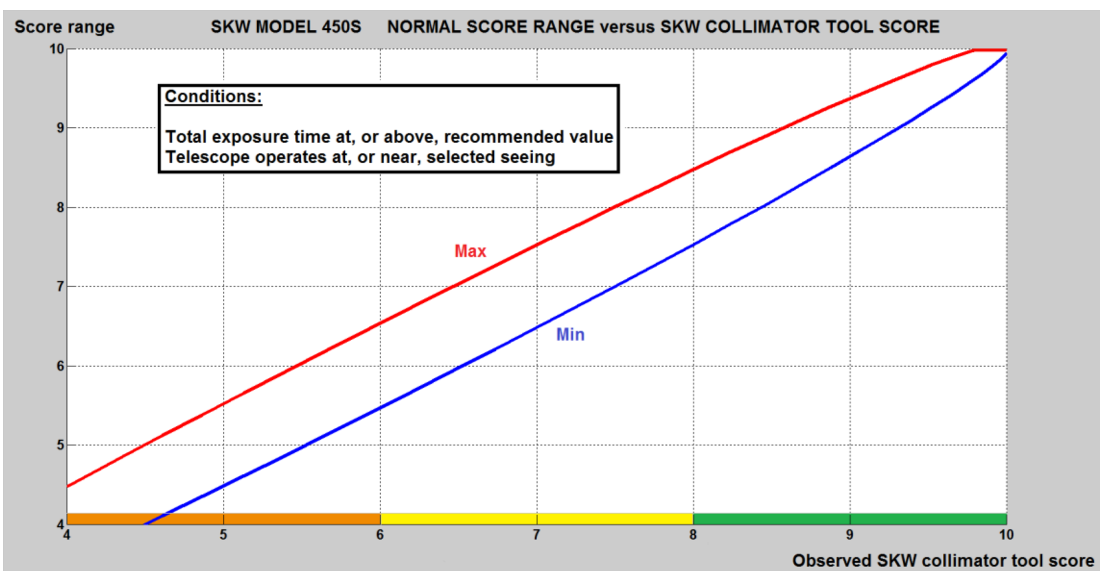
3. **Required wavefront quality for telescope alignment:**

In order for the wavefront to provide useful information and for SKW to deliver accurate enough collimation data one needs to have good and representative wavefronts. Like for the telescope PSF seeing impacts the WF as well.
The goal of this section is to discuss how and when the quality of the defocused star images (therefore the extracted WFs) are good enough for the telescope alignment job under a given seeing value.
They key parameter that is used to control the quality of the images and related WFs is the total exposure time used to take the image analyzed by SKW.
This can be done in a single exposure, or to avoid saturations as well as to deal with possible mount tracking drifts with a set of image to be stacked.
In the latter situation if any frame alignment is required one should use an image correlation technique and avoid any other processing, such as image calibration.
In general for each single image (frame) we should aim for a maximum signal level around a half to two third of the camera ADU top scale value. Of course when stacking and computing the average image this is usually done in a floating-point format and saturation level does not apply, beside for the individual frames (SKW support integer and floating-point formats FIT files). An alternate option would be to analyze with the SKW all the frames instead of stacking them. The SKW collimator tool features a handy scatter plot option, each analyzed images are displayed as a blue dot in the collimator target such one can then use the related cluster to estimate the average score value and angular position, as seen below:

The required total exposure time is a function of the scope aperture as well as the seeing. Below the recommended minimum values for SKW:



Since the seeing is always, to some level, embedded in any WF even for long exposures there are inevitable normal and expected fluctuations of the WF and therefore of the SKW collimation scores. The plot below shows the expected normal range (min and max) of the SKW collimator score for a given telescope aperture, assuming an exposure time at least equal, or longer, than the minimum discussed above. This calculation also assumes that the telescope will operate at, or near, the local seeing set in SKW by the user.



Under the above conditions those fluctuations are normal and consistent with good collimation scores and therefore telescope alignment, even if the scores change somewhat from image to image (of the total recommended exposure time).

To get an idea of seeing induced wavefront fluctuations, follow the link below:

https://www.innovationsforesight.com/Wavefront/AIWFS_SKW_Turbulent_WaveFront.mp4

This is a short video of 50 frames, 5 seconds each, analyzed by SKW, and displayed at a video rate of 5 frame/second.
The images were taken in Chili using a CDK20 (a half meter aperture telescope) with a H-alpha filter under a seeing around one arc-second in (credit: Dr John B. Hayes). The video displays, side by side, the analyzed star at best focus and the wavefront phase error 2D heat plots from SKW (red peaks, blue valleys).
The telescope aberrations have been removed by subtracting, in SKW pro version, the related wavefront found from SKW pro long exposure analysis. Those are consistent with lab measurements done previously on the same telescope using a Twyman-Green interferometer @ 633nm (PhaseCam 6000 from 4D technology).

We clearly see the short-term seeing induced speckle patterns on the star images and the resulting wavefront fluctuations. Obviously for this scope under such (good) seeing a 4 seconds exposure time is not long enough, by a long stretch. The minimum recommended value (see plot above) being around 50 seconds, at least.