Study of Vibrations at SOAR

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Abstract. The 4.1-m Southern Astrophysics Research (SOAR) telescope in Chile resembles larger optical telescopes by its thin actively controlled primary mirror, built-in tip-tilt correction, lightweight structure, and adaptive optics (AO) turbulence correction. The non-stationary vibration of the SOAR optical axis with a frequency of 50 Hz and an amplitude reaching 20–30 mas has been detected by the AO system, degrading the quality of optical speckle interferometric data. Accelerometers revealed that the 50 Hz tremor, driven by an external source, propagates within telescope structure and is strongly amplified by the response of the fast tip-tilt mirror servo system, producing characteristic elliptical beam path. The AO system also evidenced periodic components at 47 Hz in the defocus (matching the frequency of fans in electronic racks and computers) and at ∼65 Hz in the astigmatism. The latter is associated with structural resonances of the SOAR primary mirror support, apparently excited by the wind. Periodic tracking errors with typical frequencies of 0.5-2.5 Hz are mostly caused by periodic errors of the encoders, depending on their alignment, and can be amplified by the mount servo at fast tracking rates. Vibration characterization at SOAR informs similar studies at other telescopes.

Keywords: telescopes; adaptive optics; speckle interferometry.

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1 Introduction

As ground-based telescopes become bigger, they must also become lighter to remain within affordable budgets. The cost of a telescope depends on its moving mass, so making the optics and mechanical structure lighter is a necessity. However, lighter telescopes are less rigid and more prone to mechanical vibration. The lack of passive mechanical stiffness is often compensated by servo controls that effectively improve rigidity without increasing the mass. Artificial rigidity is the mainstream in modern telescope design. On this path, designers and users of large telescopes have to deal with vibrations and their mitigation.

Almost all large ground-based telescopes are equipped with adaptive optics (AO) systems for partial compensation of atmospheric distortions ("seeing") because high angular resolution is essential for reaching their full science potential. However, vibrations of the optical axis (jitter) and other wavefront distortions inside the telescope also should be compensated by AO together with the seeing. Therefore, vibrations are a relevant factor in the design and operation of astronomical AO systems. Even a tiny jitter that would be harmless in seeing-limited observations becomes detrimental at high angular resolution — in the AO instruments and in speckle interferometry.

This paper considers vibrations in the 4.1-m SOuthern Astrophysical Research (SOAR) telescope located in Chile.[1] Although by modern standards the aperture size is modest, SOAR shares many features of larger telescopes, namely the thin actively supported monolithic primary mirror (like VLT and Gemini 8-m telescopes), fast tip-tilt correction provided within the telescope itself (rather than within its instruments), and an AO system, SAM.[2] The AO technical data furnish rich information on the wavefront distortions of both atmospheric and technical origin. SOAR is actively used for diffraction-limited imaging by speckle interferometry. From the outset, SOAR aimed at reaching high angular resolution at visible wavelengths, thus complementing AO systems

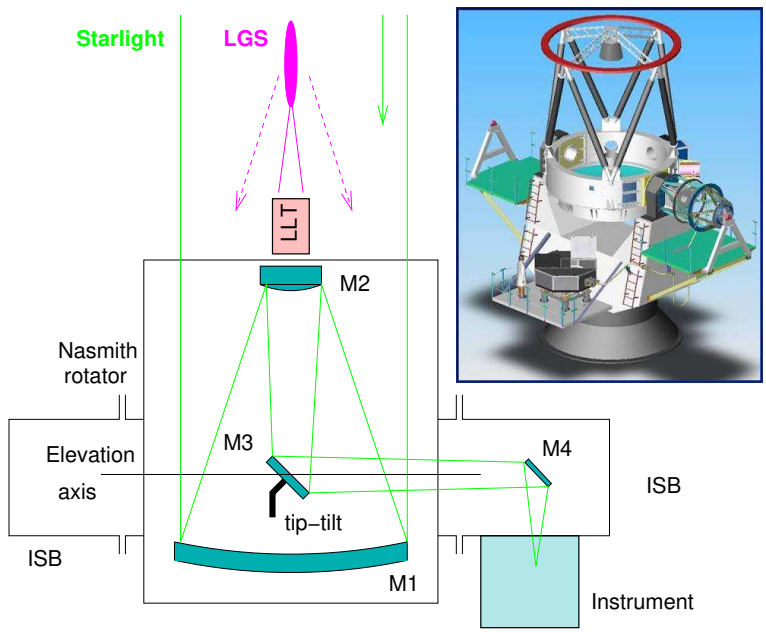


Fig 1 Scheme of the SOAR telescope. Starlight is focused by the thin primary mirror M1, reflected back by the secondary mirror M2, and directed along the elevation axis by the actuated tertiary mirror M3. At both ends of the elevation axis, the Nasmith rotators track the on-sky position angle (the mount is alt-azimuth), and the instrument selector boxes (ISBs) switch the beam between science instruments using mirrors or dichroics. The laser guide star (LGS) is produced by the small laser-launch telescope (LLT) located behind M2. The insert shows a 3D rendering of the SOAR design.

at larger telescopes that work mostly in the infrared. Main elements of SOAR relevant to this paper are introduced in Fig. 1.

Presence of a periodic 50-Hz vibration at SOAR has been noted during its commissioning.[3] It was attributed originally to the electric pick-up noise and ignored. However, in 2009, when SAM was first tested with natural guide stars, the 50-Hz tip-tilt jitter of the optical axis became obvious.[4] The amplitude of this vibration was variable and, at times, comparable to the SOAR diffraction limit (30 mas). It degraded the quality of the speckle-interferometric data. The source of this vibration remained a mystery. Several studies using accelerometers are reported below. They confirmed the presence of a quasi-sinusoidal mechanical vibration with a frequency of exactly 50 Hz at various locations within the telescope, even at its pier. The amplitude of these oscillations, however, was orders of magnitude smaller than the optical jitter, and its character was different. We surmised that the 50-Hz vibration was excited by some source outside the telescope, propagated through its structure, and amplified. Using accelerometers, we explored empirically structural resonances in SOAR, but none close to 50 Hz was found. Finally, in 2018, during telescope shutdown for mirror coating, we found the amplification mechanism: it was the fast tip-tilt tertiary mirror (M3) and its servo control. In the following 2–3 years we noted a gradual decrease of this vibration and, as a consequence, the improved quality of the speckle-interferometric data. The reason of this positive trend has not been identified.

This paper reports the character of the SOAR vibrations in § 2, accelerometry studies in § 3, and the study of M3 in § 4. For completeness, the jitter of the SOAR mount is described in § 5. In

§ 6 our findings are summarized and their relevance to other modern telescopes is discussed.

2 Wavefront Jitter at SOAR

2.1 Wavefront Statistics from AO Data

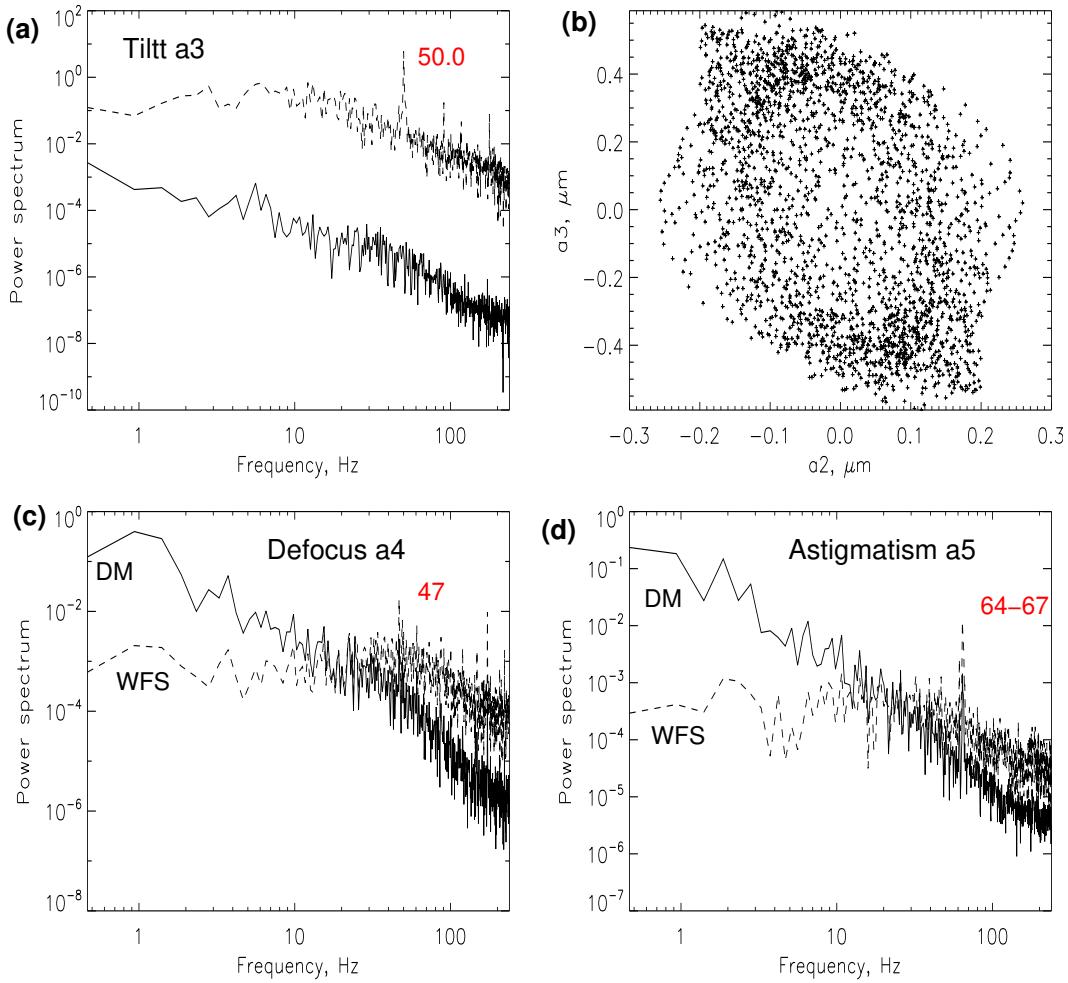


Fig 2 Representative AO data taken on 2013-09-26 at UT 00:50. Panels (a), (c), (d) show power spectra of the Zernike modes 3, 4, and 5, respectively, in the log-log scale. The dashed lines refer to the WFS signal, the solid lines to the DM signal. Panel (b) shows the trajectory of the tilts filtered in the 48–52 Hz band. The frequencies in Hz attributed to vibrations are marked in red.

The SOAR Adaptive Module, SAM, is presented in Ref. 2. High-order wavefront distortions are compensated using an UV Rayleigh laser guide star (LGS) and a 10×10 Shack-Hartmann wavefront sensor (WFS). As the LGS is located at a distance of 7 km, the WFS senses predominantly the low-layer turbulence. The tip-tilt errors are sensed by one or two quad-cell guide probes located at the input (uncorrected) focal plane of SOAR, and compensated by the fast SOAR tip-tilt mirror, M3. In 2024, SAM has been upgraded by installing a new 16×16 WFS and a deformable mirror (DM) with a larger number of actuators.[5,6]

SAM was installed at SOAR for the first time in 2009 August. Initially it used the natural guide star.[4] These tests revealed periodic components in the low-order aberrations — tilts, defocus, and astigmatism. Temporal spectra of higher-order aberrations did not show any periodic signals, only the atmospheric distortions. This diagnostic was confirmed after 2011, when SAM operated with the LGS.

During SAM commissioning and early observing runs, samples of the spot coordinates in the WFS and the DM voltages were recorded frequently. These binary records, referred to as *loop data,* were explored by an IDL code that computed Zernike coefficients measured by the WFS and applied to the DM. A typical loop data record has a length of 5 s and contains over 2000 samples (the loop cycle was 2.089 ms). The modal temporal power spectra were estimated by splitting each record into 4 portions of 512 samples each and averaging the resulting spectra in order to reduce the statistical noise. The tip and tilt of the LGS are not compensated by the DM, and the residual DM tilt is produced only by the cross-talk involved in the calculation of Zernike coefficients.

Figure 2 illustrates typical signatures of vibrations in the SAM loop data. The 50-Hz oscillations produce narrow peaks in the Zernike tilts a_2 and a_3 in most, but not all, records. Temporal filtering of these signals in the (48–52) Hz band isolates the oscillations, revealing the phase shift between a_2 and a_3; thus, the trajectory of the optical axis oscillation is elliptical. The parameters of this ellipse vary and sometimes, when the phase shift is small, it resembles a tilted line. The angular displacement α is computed from the Noll's Zernike tilts in microns and the telescope diameter D as $\alpha = (4/D)a_{2,3}$, or $0.2''$ per μm. So, the typical vibration amplitude of 0.2 μm corresponds to a 40 mas wobble of the SOAR optical axis.

The defocus term a_4 usually has a component at 47 Hz, and the $45°$ astigmatism a_5 has a broad feature around 65 Hz. The 50-Hz component is notable sometimes in the coma coefficients a_7 and a_8.

The signals of the SAM tip-tilt probes also have the 50 Hz line in their temporal spectra. However, these quad-cell sensors do not have a well-defined response coefficient between their signal and angular displacement, while their sampling rate of 100 Hz is barely sufficient (to see the 50 Hz line clearly, we interpolate the signal to 200-Hz sampling before computing its power spectrum).

2.2 Speckle Interferometry

Speckle interferometry has been started at SOAR in 2007 as a technical experiment in support of SAM,[7] but quickly evolved into an active science program.[8] The high-resolution speckle camera, HRCam, is attached to the visitor port of SAM. It takes sequences of images (data cubes) with a fine spatial sampling of 15 mas per pixel and short exposure times from a few to a few tens of ms.[9] Usually the AO loop is not closed during speckle runs for the sake of efficiency and flexibility, although occasionally faint stars were observed with HRCam and SAM in closed loop.

Vibration of the SOAR optical axis at 50 Hz with an rms amplitude of ~ 20 mas (peak-to peak image displacement 60 mas) dramatically affects speckle interferometry by reducing the signal at high spatial frequencies. A typical exposure time of 20 ms samples one full period of the oscillations, resulting in a substantial blur of the speckles. The blur shape reflects the axis trajectory: it can be nearly circular, creating a ring-like halo (Fig. 3), or quasi-linear. We took data at different position angles and verified that the blur originates upstream from the SAM+HRCam instrument. Taking speckle images with exposures time of 5 ms or shorter reduces the effect of vibration, but

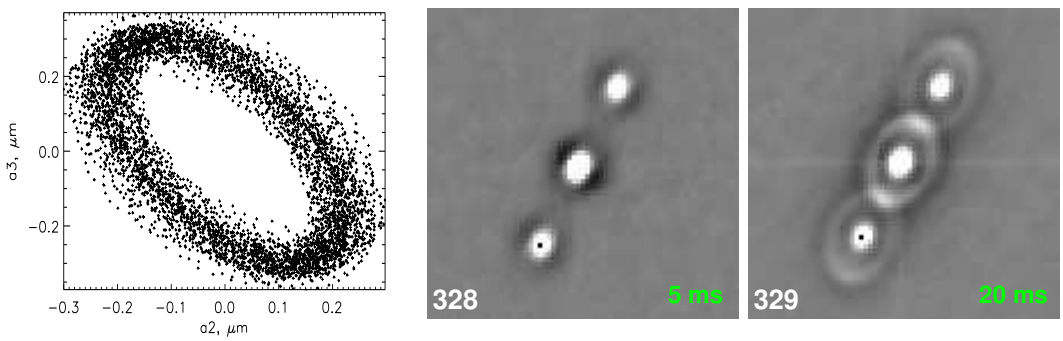


Fig 3 Influence of the 50-Hz vibrations in speckle interferometry. Left: trajectory of the line-of-sight motion with 50 Hz frequency, as recorded by SAM in closed loop on 2013-02-26 at UT 0:44. Right: autocorrelations of the speckle images of the double star HU 302 (separation $0.288''$) taken on 2013-02-16 with exposure time of 5 ms and 20 ms. A short exposure removes most of the speckle blur caused by vibrations, at a cost of reduced magnitude limit. The blur creates elliptical "disks" around the stars.

also the sensitivity. The non-stationary nature of the 50-Hz vibration means that some (lucky) speckle data are degraded less. On the other hand, non-stationarity prevents accurate calibration of the blur with single reference stars observed before or after the science targets. As noted above, the 50-Hz vibrations disappeared after 2020.

3 Accelerometry and Mechanical Resonances

3.1 Measurement Equipment

Two accelerometers have been installed at SOAR by M. Warner to monitor the behavior of its structure in normal operation and during earthquakes, which happen regularly in this region. The sensors are triaxial accelerometers LI344ALH. Their analog signals (voltages) are acquired continuously with a sampling rate of 200 Hz using the multi-channel digital-to-analog converter (DAC) model NI USB-6215. The channels 0, 1, 2 correspond to the (X, Y, Z) signals of the accelerometer installed at the SOAR top end near M2, the channels 3, 4, 5 are (X, Y, Z) signals of the second accelerometer installed at the base of the telescope pier. The sensor noise is 50 μgal/$\sqrt{\mathrm{Hz}}$, and the response is 0.65 V/gal. The broad-band noise is about 200 μgal rms. Before acquisition, the signal is filtered to pass the bandwidth of 150 Hz. With a 200-Hz sampling, this filter can pass some aliased high frequencies.

The data acquisition computer runs under Windows XP. The acquisition software is a free version of the LabView Signal Express delivered together with the DAC. It stores the data in a proprietary binary format. The data files are typically accumulated for a few days, then a new file is opened manually. The data, exported into text files, are explored here using custom software written in IDL.

For a harmonic motion with frequency ν and amplitude x, the acceleration amplitude is $a = (2\pi\nu)^2 x$. If a is expressed in gals (1 gal = 9.80665 m s^{-2}) and $\nu = 50$ Hz, the amplitude in meters is

$$x/a = 9.80655(2\pi\nu)^{-2} = 9.363\,10^{-5}\ \ \mathrm{m/gal}. \tag{1}$$

A 50 Hz vibration with 1 μm amplitude corresponds to 0.01 gal or 6.5 mV voltage, considering the response of 0.65 V/gal.

3.2 Characteristics of the 50 Hz Acceleration

We explored signal of the accelerometer installed near SOAR M2 during three nights of September 25-27, 2013, when SOAR was in regular operation. The telescope movement in elevation slowly changes the Y and Z voltages due to the varying gravity direction. These trends were subtracted, and the power spectra of small data segments were computed.

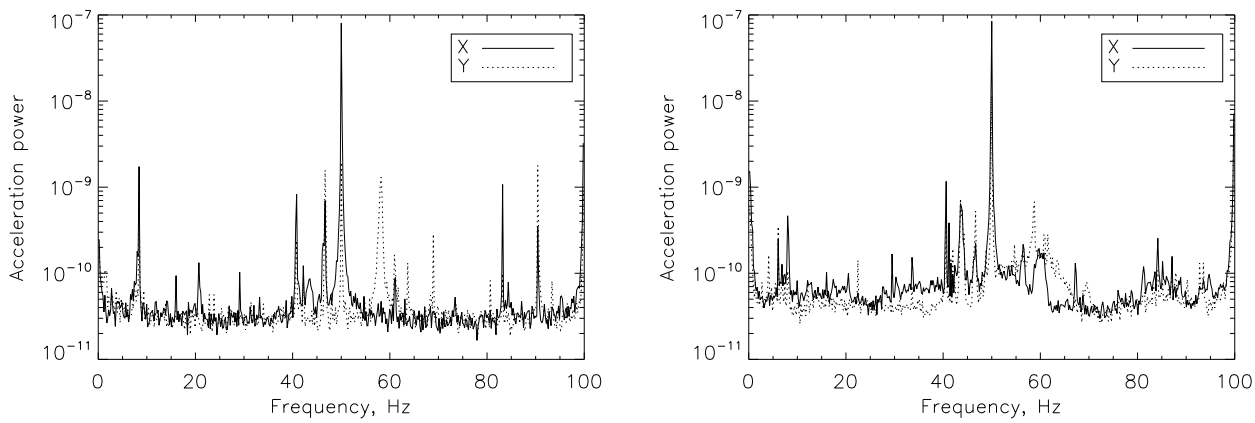


Fig 4 Power spectra of acceleration at M2 recorded around UT 4h on 2013-09-25 (left) and 2013-09-27 (right). Solid line – along X, dashed line – along Y.

Power spectra of the accceleration in X and Y directions (perpendicular to the telescope axis) near M2 are shown in Fig. 4 for representative periods on two nights. The most prominent line is at 50 Hz. It is stronger in X than in Y, and is also present in Z. On September 25 we saw a line around 8 Hz (which could be an alias) and some weaker lines. The 47 Hz line is often seen in the defocus term of SAM, and we note its presence in the acceleration as well. Different data portions have different spectra, but the 50-Hz line is present almost always.

It is known that the motion of the SOAR optical axis with 50-Hz frequency in X and Y is correlated and its trajectory is elliptical. However, the two components of the acceleration do not show such correlation, and the (X,Y) trajectory resembles a scatter plot. The lack of correlation proves that the 50-Hz accelerometer signal is not an pickup noise and that it is not proportional to the motion of the optical axis.

The amplitude of the 50-Hz acceleration changes with time, without obvious dependence on the telescope position. Figure 5 shows the amplitude of the 50-Hz acceleration in X during 12 minutes when the telescope pointed several targets. Between the spikes that coincide with slews, the amplitude does not remain stable, varying between 1 and 5 μV.

The acceleration at the pier of SOAR was examined using the same tools. Long data segments allow us to measure the width of the 50-Hz line which is inversely proportional to the temporal coherence of this signal. The half-width of the line is about 0.25 Hz both at M2 and at the pier base (Fig. 6). The line width remains the same when the telescope is tracking and when it is stationary (parked). The bandpass-filtered signal at 50 Hz shows oscillations in each coordinate with variable amplitude resembling chaotic interference (beating) between two close frequencies.

As noted above, the amplitude of the 50 Hz acceleration changes with time, alternating between "calm" and "noisy" periods. Analysis of the amplitude during several hours did not reveal any

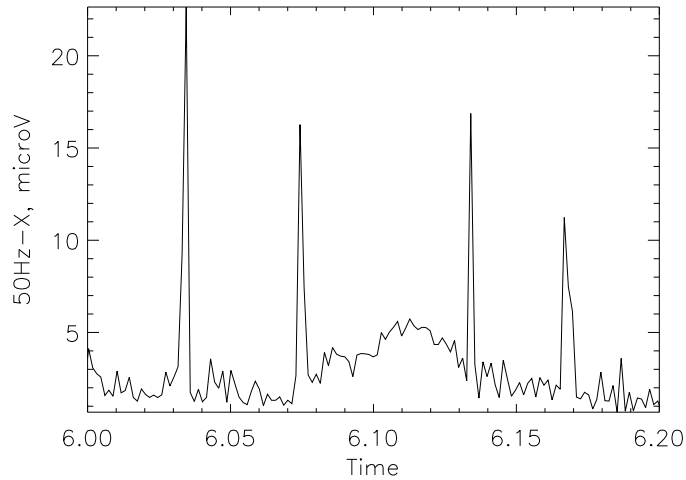


Fig 5 Amplitude of the 50-Hz acceleration in X at M2 vs. UT time on 2013-09-25. The spikes occur when the telescope slews to a new target.

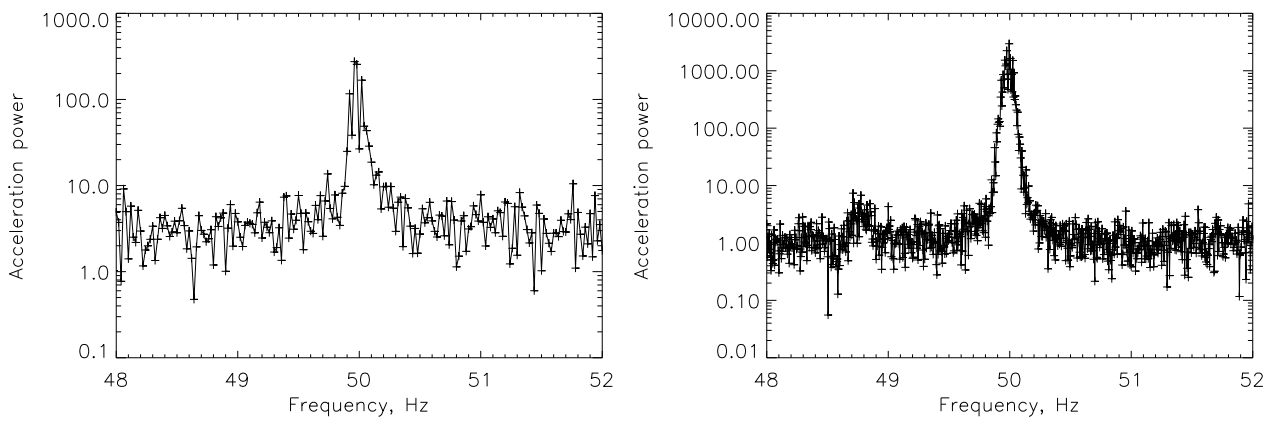
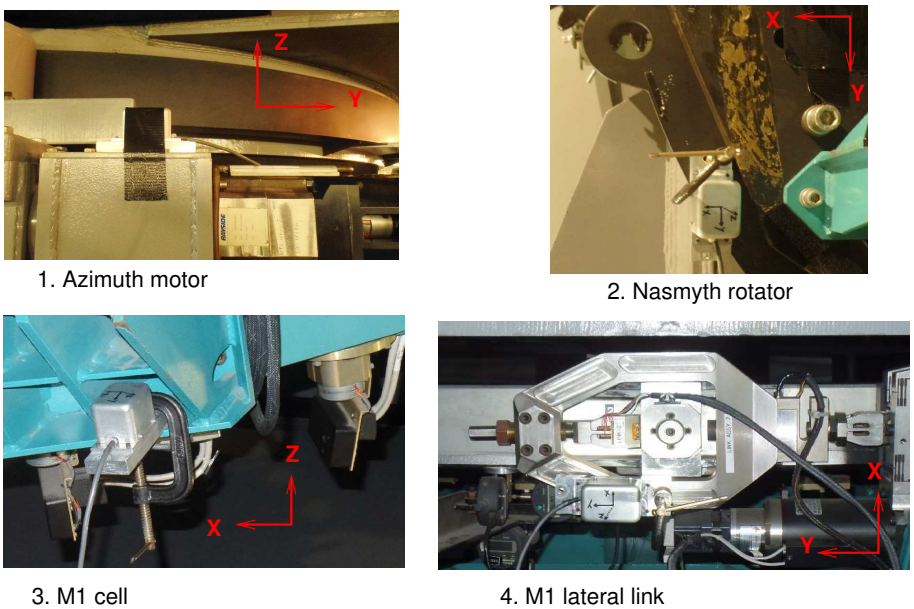


Fig 6 Fragments of high-resolution temporal spectra of acceleration near 50 Hz. Left: acceleration at the SOAR pier in Y on 2013-09-27 starting at 4h UT. Right: acceleration at M2 on 2013-09-27 starting at 9.8h UT when the telescope was parked.

regular patterns or clues. There is only a very loose correlation between amplitudes of the 50-Hz acceleration at M2 and at the pier; the amplitude at the pier is approximately two times less than at M2.

If SOAR vibrated at 50 Hz as a solid body with an amplitude of 1 μm (6.5 mV acceleration) at the top end, its axis would move with an angular amplitude of 45 mas (tube length of 4.5 m assumed). However, as can be inferred from Fig. 5, the actual worst-case amplitude of the 50-Hz transverse acceleration at M2 is $\sim$5 μV, three orders of magnitude smaller. So, if the 50-Hz acceleration is indeed the source of the 50-Hz tip-tilt vibration, it should be strongly amplified somewhere.



1. Azimuth motor

2. Nasmyth rotator

3. M1 cell

4. M1 lateral link

Fig 7 Locations of the accelerometer during vibration tests on 2015-09-25.

3.3 Structural Resonances

Pursuing the idea that the 50 Hz vibration is excited externally and somehow amplified within the telescope structure, I explored mechanical resonances at SOAR. On October 5, 2014, a portable accelerometer was placed at various locations on the Instrument Selector Box (ISB) at the optical Nasmith focus of SOAR to probe whether it vibrates or not. The 50-Hz line was absent in the records, instead we saw a 47-Hz signal presumably matching the frequency of fans in the electronic racks (asynchronous motors). However, these tests were done without telescope tracking.

Table 1 Accelerometer locations and orientation on 2015-09-25

N	Location	X	Y	Z	Frequencies
1	Azimuth motor	Rad	Az	Up	50
2	Nasmyth rotator	Az	Down	Rad	(20-60); 50
3	M1 cell	Az	Rad	Up	(20-30); 50
4	M1 link	Up	Az	Rad	(60-80); 66
5	Pier	Down	Az	Rad	(20); 50

On September 25, 2015, we studied the effect of telescope tracking. The same portable accelerometer (normally installed at the base of the pier) was connected by a long cable and placed at various locations. Simultaneous data from the second accelerometer installed behind the M2 were recorded as well. Figure 7 shows the first four tested locations. Table 1 lists the locations and the directions of the accelerometer axes (Rad is parallel to the telescope optical axis, Az is directed along azimuth). At each location, one or more data records of 3 min. or longer were taken. Figure 8 illustrates the results summarized below.

At the azimuth motor (location 1), the 50-Hz peak was seen in the signals of all axes, with the telescope tracking or not. The motor itself is therefore not responsible for exciting the 50 Hz vibration. The rms signal was $\sim$0.6 mV. In the second record taken at the same location (with

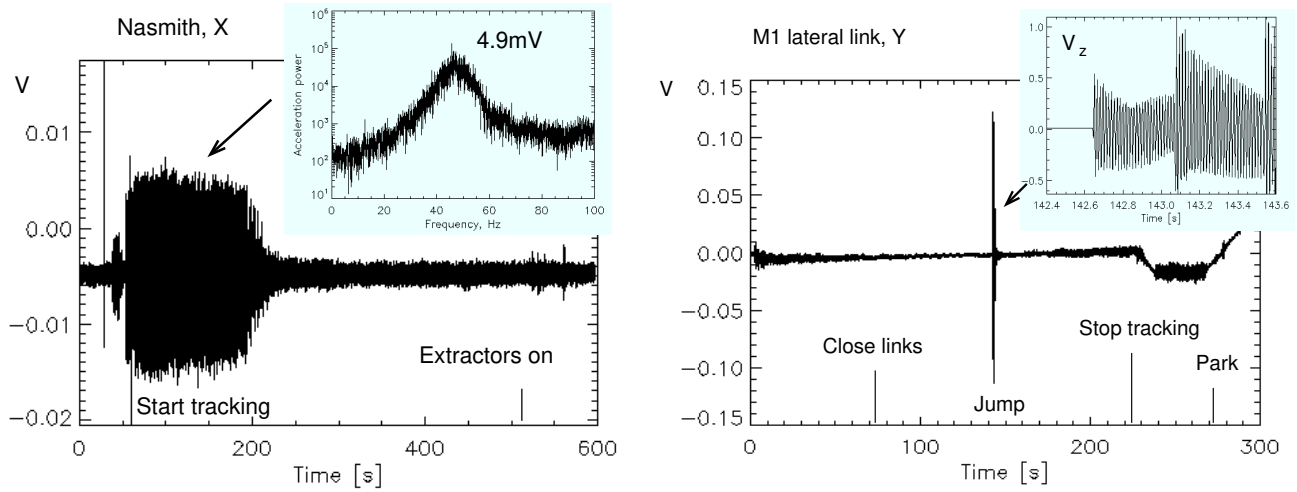


Fig 8 Accelerometry on 2015-09-25. Left: acceleration at the Nasmith rotator along X with temporal spectrum during the vibration episode. Right: Acceleration at M1 lateral link in Y with an artificial earthquake; the insert shows Z-oscillations during the quake.

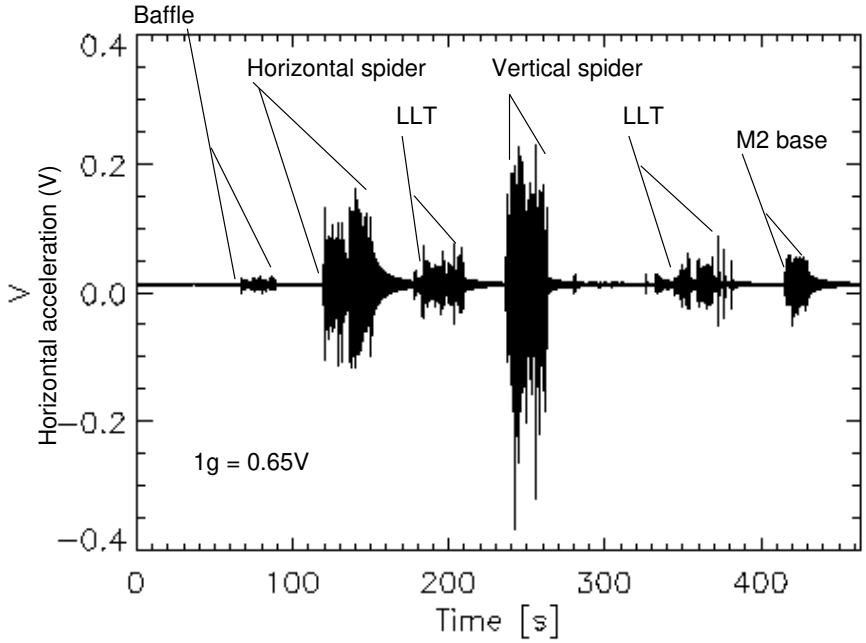


Fig 9 Full record of the X-acceleration at the SOAR M2 taken on 2015-11-12. Moments when the structure was tapped are indicated.

telescope moving in elevation) the 50 Hz line was absent, but weak lines at 47 Hz and 83 Hz appeared, while the rms signal in X and Y was smaller, 0.25 mV.

In the 10-min. record taken at the Nasmith rotator (location 2), there is a 100-s period with strong vibration (4.9 mV rms in X, i.e. in azimuth), see Fig. 8 left. It began after the telescope started tracking; its spectrum had a broad peak between 30 and 60 Hz. The increased vibration could be caused by some motor or compressor that work intermittently. When it stopped, the telescope was still tracking, but the rms signal dropped to 0.45 mV, with only a weak line at 50 Hz. At the end of the record, the fans extracting air from the dome were turned on, without any effect on vibration. During the vibration episode, the accelerometer at M2 increased the rms only by a factor of two, not by an order of magnitude as at the Nasmith rotator.

The accelerometer attached to the M1 cell (location 3) recorded relatively small accelerations (1.4, 0.4, and 0.6 mV rms at X, Y, Z, respectively) independently of the telescope tracking. However, this record also contains a "vibration episode" lasting about a minute. During this period, the largest acceleration was in Z, and its spectrum had a broad peak at 20–30 Hz. During the rest of the record, only a narrow 50-Hz line was seen.

Acceleration at the M1 lateral link (location 4) revealed an interesting phenomenon. The amplitude was relatively small (1.1, 1.6, 1.5 mV rms in X, Y, and Z), and it did not increase when the servo loop of the lateral links was closed. A narrow line at 66 Hz was present only in the X-axis (vertical). In the middle of the record, people standing on the Nasmith platform jumped, emulating an earthquake. This produced large accelerations in X and Z (perpendicular to the link axis). The acceleration amplitude in Z exceeded 1 gal, and its power concentrated between 60 and 80 Hz, indicating resonant oscillations. The maximum at $\sim$66 Hz matches the broad peak in the astigmatism temporal spectra detected with SAM. This vibration is therefore associated with the structural resonances of the M1 and its support. During normal telescope operation, these resonances can be excited by the wind buffeting. Quite surprisingly, the artificial earthquake had no effect on the accelerometer located at M2.

Finally, the accelerometer was clumped to the telescope pier inside the dome (location 5). As expected, the acceleration was small (0.2, 0.2, 0.5 mV rms in X, Y, Z). During this record, a minor natural tremor occurred, causing some oscillation around 20 Hz. Apart from the tremor, only the 50 Hz line was detected.

Resonances at the M2 unit were probed on November 12, 2015. The acceleration was recorded during 464 s while I tapped at various elements around the secondary mirror M2. The laser launch telescope (LLT) is attached behind the M2 unit, which is connected to the telescope top ring by four spiders. The M2 is surrounded by a conic baffle. The telescope was in horizontal position, the X axis of the accelerometer was oriented horizontally.

Figure 9 shows the full-length record in the signal in X with indication of time and place of the artificial excitation. In all cases, tapping excited a resonance at 14.4 Hz in the X and Y axes, and this quasi-sinusoidal oscillation decayed approximately exponentially ($1/e$ decrement of 6–10 s). The accelerations in X and Y were perfectly correlated and of similar amplitude, so the vibration was directed at 45° relative to the spiders. There was no phase shift (the XY trajectory was linear), and the 14.4 Hz resonance was not detected in the Z axis. A weaker resonance at 51.5 Hz was seen when the LLT or vertical spider were tapped.

In summary, the accelerometer tests did not reveal any structural resonances that could explain the amplification of the 50 Hz vibration. However, the resonances of the M1 support structure around 66 Hz, likely associated with the wavefront oscillation in astigmatism, were documented.

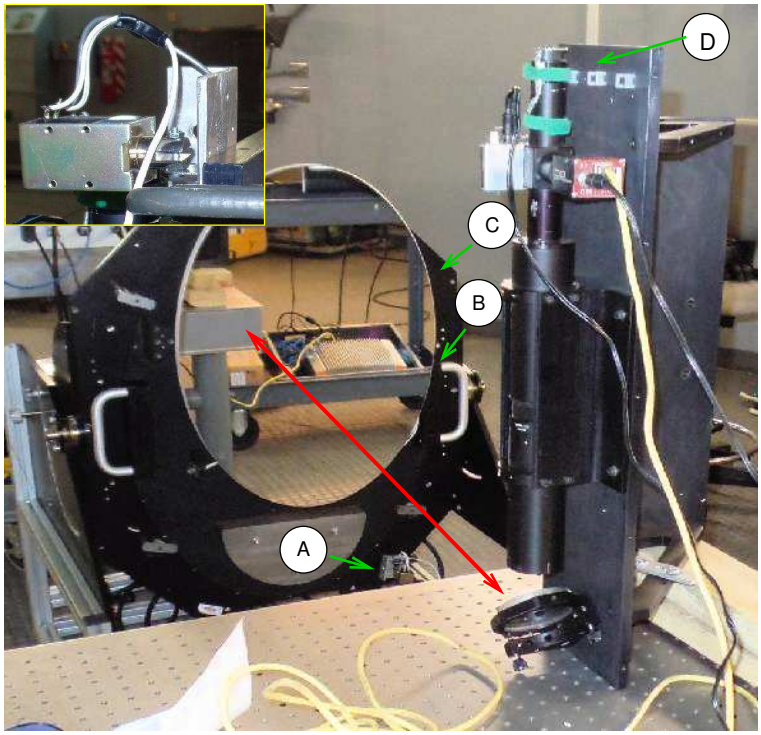


Fig 10 Configuration of the M3 optical test on 2018-11-23. The optical path is shown in red. The insert on the top-left shows the shaker. Letters A–D indicate locations where the shaker was clumped.

4 Study of the Tip-Tilt Mirror M3

The SOAR fast tip-tilt mirror, M3, is suspended on a 2-axis pivot and controlled by the digital servo system that replaced the original analog circuitry.[10] The mirror tilts relative to its base are measured by four inductive sensors. The servo system is designed to damp the natural resonance of the M3 suspension and to provide a bandwidth up to 50 Hz. Potentially, the M3 servo could amplify the 50 Hz frequency because it is near the limit of its working band.

During the SOAR coating shutdown in 2018 November, the M3 response to mechanical excitation at 50 Hz was tested. The M3 unit was mounted in its test rig located on the dome floor, with its servo system active as in normal operation. The mirror angles were measured by a collimated laser beam emitted by the dome-probe device used previously for monitoring seeing inside telescope enclosure.[11] It produces a 4-cm diameter beam. The beam is directed to M3, reflected back, and detected by the CCD camera in the same device (Fig. 10). The dome probe is fixed to the optical table, and a 45° flat folding mirror in a kinematic mount allows centering the image of the reflected beam on the CCD. The software written in python enables fast acquisition of the spot images, measurement of centroids, and their statistical analysis (rms, power spectrum). Sequences of centroids can be saved for further study. In these tests, we used the exposure time of 5 ms (frame rate 200 Hz), sampling the 50-Hz signal adequately.

Mechanical vibrations with a frequency of 50 Hz were generated by an improvised shaker clumped to the M3 unit at different locations. The shaker is based on the Ledex latching solenoid (model TDS-K12SB, DC-12V). The core of the solenoid is retained by the permanent magnet and is released when the voltage of $\sim$10 V of adequate polarity is applied to cancel the magnetic field.

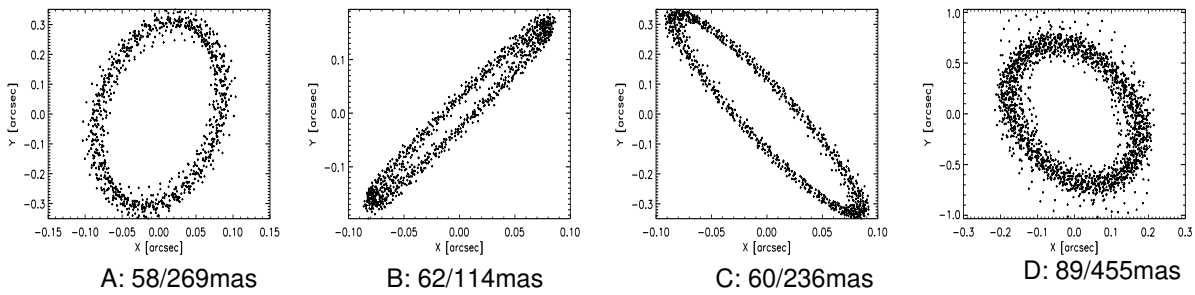


Fig 11 Trajectory of the M3 optical axis motion with 50 Hz frequency excited by the shaker at locations A-D. The numbers indicate rms amplitude of the cenrtroid motion in X and Y (in mas).

The solenoid was connected to the 50-Hz AC voltage with adjustable amplitude derived from a reducing transformer. The core was fixed to an aluminum bracket which, in turn, was clamped to the structure. The coil was connected to the bracket flexibly, allowing its motion. The core position inside the coil was chosen to obtain maximum vibration. Motion of the solenoid at 50 Hz creates a reaction force applied to the base on the order of 1 newton for a driving voltage of 7–9 V used in these tests.

As both the M3 cart and the optical table were placed on the dome floor, any motion of persons inside the dome affected the optics. The tests were conducted on 2018-11-21 and 2018-11-23 without people at the dome floor, and an rms beam motion as small as $0.1''$ was achieved. The residual slow mechanical perturbations caused by the floor instability did not affect our tests. Several records of the M3 internal position sensors with 20 kHz sampling were taken as well. During these tests, SOAR was powered by a generator, and the line frequency was 50.4 Hz.

The 50-Hz vibration excited by the shaker is manifested by a strong peak in the power spectra of the dome probe signal; when the shaker is switched off, the peak disappears. Figure 11 shows representative trajectories of the reflected beam in 10-s segments of the dome probe data with the shaker clumped at different locations. The signal was filtered in the 47–53 Hz band. The numbers indicate the rms centroid motion in X and Y directions. These angles are $\sim$15 times larger than the equivalent image motion at the SOAR focus (M3 is located at 4.2 m before the focus, while the effective focal length of SOAR is 68 m). Obviously, the phase shift between X and Y oscillations and their amplitude depend on the location of the vibration source. One might question these results because narrow-band filtering of noise also produces a quasi-sinusoidal signal. However, when the shaker is turned off, the XY trajectory resembles a random scatter with an order of magnitude smaller amplitude of 5–9 mas. When the shaker is attached to the dome probe (location D), the 50-Hz vibration appears again.

When the beam trajectory is computed separately for several 10-s fragments of one dome probe signal record, the trajectories and amplitudes do not remain the same, indicating that the M3 oscillation is excited and damped randomly. However, the orientation of the ellipse, governed by the phase shift between X and Y, is approximately preserved.

The 50-Hz oscillations excited by the shaker are also apparent in the signals of the M3 position sensor recorded during these tests. The trajectory of the optical axis deduced from the sensors is also elliptical. An earlier record of the M3 position sensors was taken on 2014-07-08, when the telescope was tracking. The M3 elevation angle power spectrum had a peak at 50 Hz (as well as

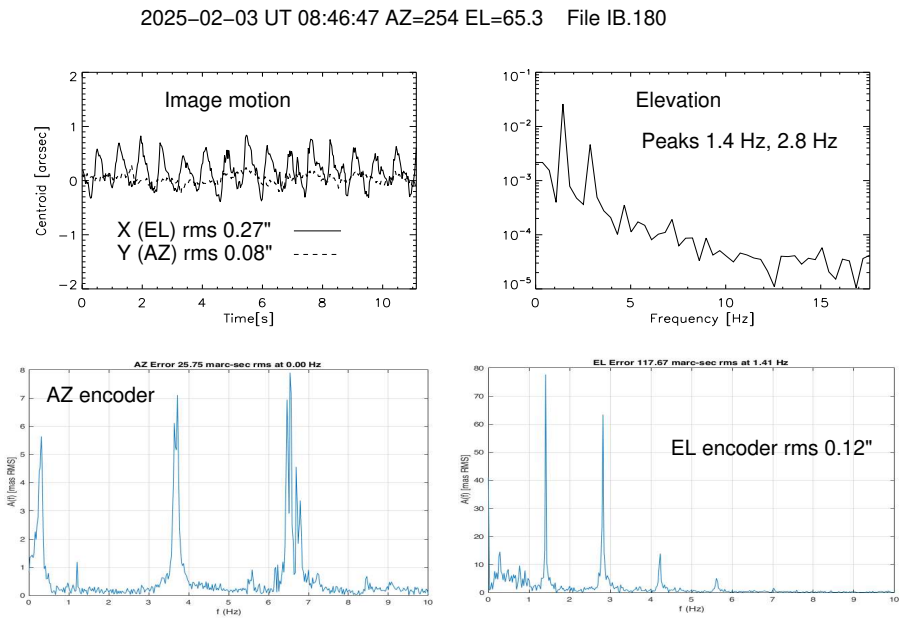


Fig 12 Tracking errors of the SOAR mount deduced from the speckle data cubes. The upper panels show the trajectories of the image centroid in X and Y and the power spectrum of the X-motion (X is directed along elevation). The lower panels show the power spectra of the mount jitter in azimuth and elevation derived from the encoder signals by B. Cancino for the same time period.

smaller peaks at 47 and 65 Hz), while the azimuth angle had a strong peak at 100 Hz. The latter could be of electrical origin (feed-through of the power supply pulsation?).

5 Mount Jitter

For completeness, this section covers image oscillations produced by tracking errors of the SOAR mount. Speckle interferometry observations collected a rich material for such study. The data cubes are typically taken with exposure time of 25 ms and contain 400 or 600 individual images (10–15 s duration). Centroids of the star in each frame are computed by the standard speckle pipeline and saved. In most cases, the rms centroid motion in each speckle cube is $\sim 0.3''$. Its power spectrum is dominated by low frequencies, as expected for image shifts produced by seeing and, occasionally, wind shake. In some observing runs, however, quasi-periodic image displacements caused by the mount tracking errors are present.

A large jitter in the azimuth direction has been encountered on February 26-27, 2024. It appeared and disappeared sporadically, reaching a $2''$ amplitude in the worst cases. The jitter was stronger at low telescope elevation. The reason of this jitter has been identified: during the daytime technical work on the mount, one of the tachometers of the azimuth motors was connected wrongly. It should be mentioned that for several years SOAR operates with three azimuth motors instead of the nominal four, which affects the backlash compensation. Furthermore, in 2026 another azimuth motor failed and problems in the motor controllers were discovered. These technical faults directly affect the SOAR tracking quality.

A more typical situation was encountered on February 1-3, 2025, when speckle observations were conducted in the morning hours. A quasi-periodic oscillation in the elevation direction was

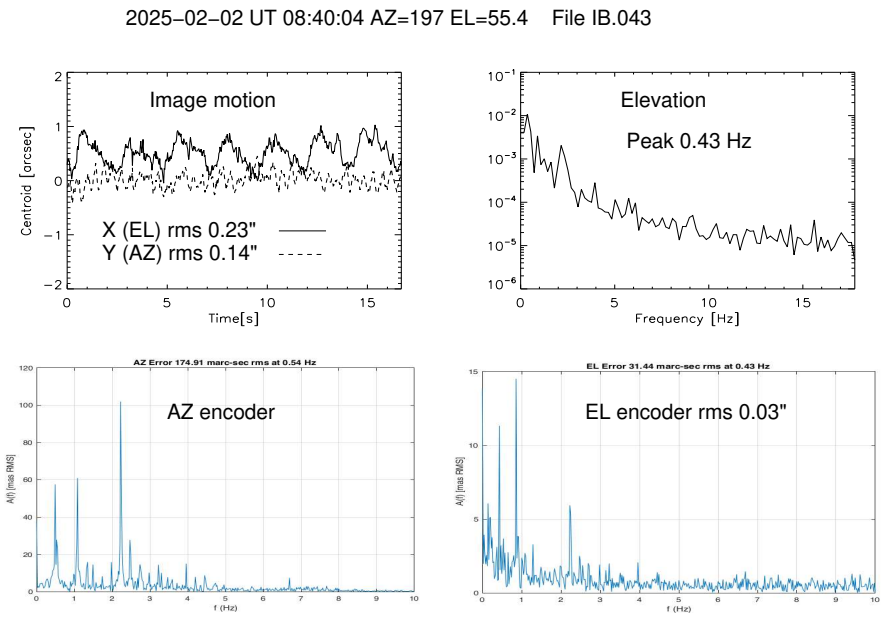


Fig 13 Tracking errors of the SOAR mount deduced from the speckle data cubes (see Fig. 12).

noted. Its amplitude and frequency substantially depended on the telescope pointing. Two examples are presented in Figures 12 and 13. In the subsequent analysis, shifts of the image centroid were transformed (rotated) to elevation (X) and azimuth (Y) directions. Signals of the mount encoders recorded in the SOAR telemetry system were examined by B. Cancino as additional evidence.

When the telescope points east or west, the tracking speed in elevation is the largest. The frequency and amplitude of the elevation oscillation are also larger. The periodic jitter is caused by the encoders. The periods of encoder tapes are $8.904''$ and $20.24''$ in elevation and azimuth, respectively. The sine and cosine encoder signals are interpolated on a 4096-point grid, and any signal distortion caused by an imperfect alignment of the tape-reading head translates into periodic position errors. The bandwidth of the mount servo is about 1 Hz. At fast tracking, the first and second harmonics of the periodic encoder errors are close to or beyond the cutoff frequency of the mount servo, so they are amplified rather than compensated. In Fig. 12, the rms centroid motion in elevation is $0.27''$, while the rms tracking error measured by the elevation encoders is less, $0.12''$. In contrast, the centroid motion in azimuth is only $0.08''$ rms, and the periodic errors in the azimuth encoders are also much smaller. Note that during these observations the wind speed was low.

Figure 13 presents similar data for the case when SOAR pointed in the southern direction and the tracking in elevation was slow. The motion in elevation is still quasi-periodic and has a comparable amplitude of $0.23''$. However, the dominant peak at 0.43 Hz is now within the mount servo bandwidth, and the tracking servo faithfully follows the encoder signals. As a result, the rms tracking error in elevation reported by the encoders is very small.

Although the periodic tracking jitter is slow compared to the 25-ms exposure time used in speckle interferometry, it causes measurable degradation of the speckle contrast. A harmonic motion as in Fig. 12 corresponds to the maximum speed of $2.4''$ per second that blurs the speckles up to 60 mas, twice the diffraction limit. The actual speckle power spectra clearly show this attenuation in the direction parallel to the jitter.

Periodic tracking errors are noted sometimes by the SOAR operators. Typical observations use fast guiders to compensate both the wind shake and the atmospheric tilts. The guiders correct the relatively slow periodic tracking errors using the actuated M3 mirror. Periodic tilts in M3 are often perceived by the operators as a guider malfunction, while in fact they demonstrate the opposite: the guiding system works well. Without fast guiding, periodic tracking errors can cause appreciable image elongation. Even a moderate jitter with an rms amplitude of $\sigma = 0.3''$ causes peak-to-peak image displacement of $2\sqrt{2}\sigma = 0.85''$. When the guiders are not used or operate with long exposures, stars in the SOAR science images can be elongated by the mount jitter.

On September 10, 2025 the elevation encoders were tuned and their periodic errors were reduced, diminishing also the periodic tracking oscillations. This was confirmed by the speckle data of September 7 and 11, 2025, that show a substantial reduction of the jitter after the encoder tuning. On September 11, the rms centroid motion in both directions was about $0.15''$. However, tuning of the encoders does not remain stable, being affected by seismic tremors, so it needs regular attention by the telescope crew.

6 Summary and Discussion

This paper relates the story of the discovery and study of mysterious 50-Hz vibration of the SOAR optical axis. Detection of acceleration at this frequency even at the base of the telescope pier made it clear that the driving source was external to the telescope. It could be a transformer or some synchronous motor. One could actually feel this vibration by touching lightly the dome walls. This line in the acceleration power spectrum had a width of 0.25 Hz and its amplitude was not stationary. After 2020, the vibration was no longer perceptible in the speckle-interferometric data. The 50-Hz acceleration itself was too small compared to the typical wobble amplitude of the optical axis (20–30 mas). This wobble with its characteristically elliptical trajectory was produced by the fast til-tilt mirror M3. Its servo system apparently amplified the external perturbation, causing phase-shifted motion in X and Y. It cannot be excluded that the 50-Hz excitation originated within the M3 unit itself (e.g. in the motor driving its turret). The true source of the 50-Hz acceleration and the reason for its gradual disappearance after 2020 still remain unidentified.

The Lowell Discovery Telescope (LDT)[1] is a cousin of SOAR with similar thin primary mirror, optical truss, and mount. However, the LDT has a larger secondary mirror and is not equipped with actuated tip-tilt mirror (all instruments are located on-axis at the Cassegrain focus). The LDT is also frequently used for speckle interferometry, but it does not suffer from the 50-Hz wobble, as communicated by their speckle team. This is yet another indirect evidence that the 50-Hz wobble at SOAR was generated by its M3 unit.

Several experiments with accelerometers described here revealed structural resonances of SOAR, e.g. the 16-Hz resonance of the M2 unit and the 65-Hz resonance of the M1 support. The latter is detected in the astigmatism coefficient measured by the AO system in normal operation. However, the amplitude of this vibration is too small to affect the delivered resolution. The same is true for the tiny focus oscillations at 47 Hz excited by vibration from fans. The M2 structure had a mechanical resonace at 20 Hz reported in Ref. 3 before addition of the LLT and its electronics that shifted this resonance to 16 Hz.

Periodic tracking errors are common to many telescopes, and SOAR is not an exception. A very strong tracking jitter at SOAR was caused occasionally by malfunction of the drive system (motors

[1] https://lowell.edu/research/research-telescopes/lowell-discovery-telescope-ldt/

and their controllers). Smaller oscillations with frequencies of 0.2-2.5 Hz are encountered routinely due to periodic errors of the encoders. The frequency of these oscillations is directly proportional to the tracking speed, while their amplitude depends sensitively on the alignment of the encoder heads. The alignment is regularly perturbed by tremors, requiring careful monitoring and/or a better mechanical design of the encoder support. Tracking oscillations are typically corrected by the fast guiders; otherwise, they can cause noticeable elongation of long-exposure images. These oscillations also affect the quality of speckle data by smearing speckles in one direction.

The methods outlined here to characterize SOAR vibrations, namely analysis of AO real-time data and accelerometry, can be applied to other telescopes. Excitation of structural resonances by "artificial earthquakes" is an efficient way of their identification. However, the optical study of the M3 unit relied on a non-standard equipment. To our knowledge, speckle-interferometric data were used here to evaluate tracking for the first time.

The diffraction-limited resolution λ/D delivered by AO or speckle interferometry becomes finer with increasing telescope diameter D, placing stronger requirements on vibration mitigation and tip-tilt errors. The use of LGS does not help in tip-tilt compensation which relies on natural and necessarily faint guide stars. AO systems at large telescopes are normally designed for correction of atmospheric tilts, and fast vibrations of optical axis may undermine their performance. In principle, fast motions can be sensed by accelerometers or seismometers (see Ref. 12 and references therein), alleviating requirements on guide stars. This idea has been advocated a long time ago but, so far, has not been realized. The lesson learned from SOAR is that telescopes do not vibrate as solid bodies, so inertial sensors are of little help for tilt correction.

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