Making FORS2 Fit for Exoplanet Observations (again)

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For about three years, it has been known that precision spectrophotometry with FORS2 suffered from systematic errors which made quantitative observations of planetary transits impossible. We identified the longitudinal atmospheric dispersion corrector (LADC) as the most likely culprit, and therefore engaged in a project to exchange the LADC prisms with the uncoated ones from FORS1. This led to a significant improvement in the depth of the FORS2 zero points, a reduction in the systematic noise, and should make FORS2 competitive again for transmission spectroscopy of exoplanets.

Over the last two decades remarkable progress has been made in understanding the diversity of planets in the Galaxy from the success of radial velocity and transit surveys. Transiting planets allow both their masses (if radial velocities are also available) and radii to be measured, leading to bulk densities and compositions. However, in order to truly understand planetary systems we need a method of obtaining the spectra of exoplanets, thereby probing the composition and structure of their atmospheres. Luckily, transiting systems allow such measurements, even though we cannot resolve the star and planet spatially; rather we can temporally resolve light from the star and planet during transits, when the planet passes in front of its host.

The transit depth obtained by transmission spectroscopy of the host star provides a direct measurement of the planet-to-star radius ratio as a function of wavelength. The effective size of the planet varies due to wavelength-dependent opacities in the planet's upper atmosphere, and a transmission spectrum can therefore probe the atomic and molecular species in its atmosphere causing such radius variations (Seager & Sasselov, 2000; Brown, 2001; for a recent review, see Burrows, 2014). For many years, space-based observations with the Hubble Space Telescope (HST) and Spitzer Space Telescope were the only source of exoplanet spectra.

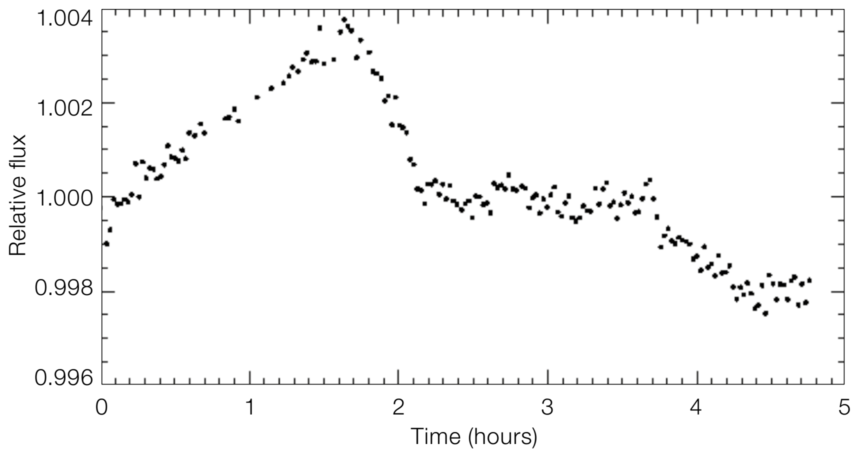
This all changed after pioneering observations of the exoplanet GJ 1214b using the Focal Reducer / low dispersion Spectrograph (FORS2) instrument proved that precise transmission spectra could be obtained from ground-based instruments (Bean et al., 2010). Their paper used the FORS2 multi-object spectroscopy capability with the mask exchange unit (MXU) to perform differential spectrophotometry, i.e., observing time-series spectra of the target star simultaneously with many comparison stars, thus correcting for variations in the Earth's atmospheric throughput. Since then, such observations have been performed routinely using different instruments and telescopes, and have even proved successful at infrared wavelengths (e.g., Snellen et al., 2010; Bean et al., 2011; Gibson et al., 2013a,b; Crossfield et al., 2013; Stevenson et al., 2013; Schlawin et al., 2014). As future space-based observatories will focus on the infrared, ground-based instrumentation will be the only way to probe the optical transmission spectra of exoplanets. This is a crucial wavelength regime for the understanding of the physics of exoplanet atmospheres, and in particular for the determination of the mean molecular weight of the atmosphere and atmospheric scale height from measuring the Rayleigh scattering slope.

A cause for alarm

Despite the pioneering observations by Bean et al. (2010; re-analysed in Bean et al., 2011), no other exoplanet transit has been published so far from FORS2 data and it seems that there is a consensus in the community that FORS2 is no longer suited for the study of planetary transits. The fact that Bean et al. were successful in their observations is thought to be due to a combination of factors, i.e., short transit time, small variations in airmass during the observations, good weather, and more generally, the best of luck and great skill. This is of course a worrying situation, especially since the Gemini Multi-Object Spectrograph (GMOS) instruments on the Gemini telescopes, which are rather similar to FORS2, are among the most successful instruments to date for measuring transmission spectra from the ground (Gibson et al., 2013a, b; Crossfield et al., 2013).

The reason for this problem with FORS2 appears to lie with the unexpectedly high systematics in the differential light curves

Figure 1. Differential light curve of the source WASP 4 obtained in the *z*-band using FORS2 in MXU mode in December 2011. Most of the variations seen in this plot are attributed to variations in throughput within the FORS2 LADC.



that were obtained, which turned out to be impossible to calibrate out reliably (at least to the level of ~ 10^{-4} as required in the transit depth precision for a hot Jupiter; see Figure 1). The main source of these instrumental systematics is most likely the LADC on FORS2. From visual inspection, the anti-reflection coating of this optical element is known to have degraded over time. Berta et al. (2011) reported these systematics: "Moehler et al. (2010) found that the LADC on the telescope has surface features that affect its sensitivity across the field of view. Because the LADC is positioned before the field rotator in the optical path and rotates relative to the sky, individual stars can drift across these features and encounter throughput variations that are not seen by the other comparison stars."

The design of the FORS2 LADC consists of two prisms of opposite orientation that are moved linearly with respect to each other, between 30 mm (park position) and 1100 mm. The forward prism performs the dispersion correction, while the second prism corrects the pupil tilt, so that what remains is a variable image shift depending on the distance between the two prisms (Avila et al., 1997).

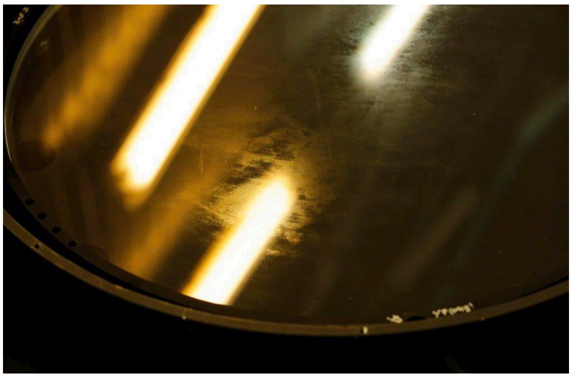


Figure 2. Photograph of the FORS2 LADC prism (with coating) after removal from the instrument. The damage to the coating in various places is obvious. Note that the bright regions are reflections of the neon lights on the ceiling.

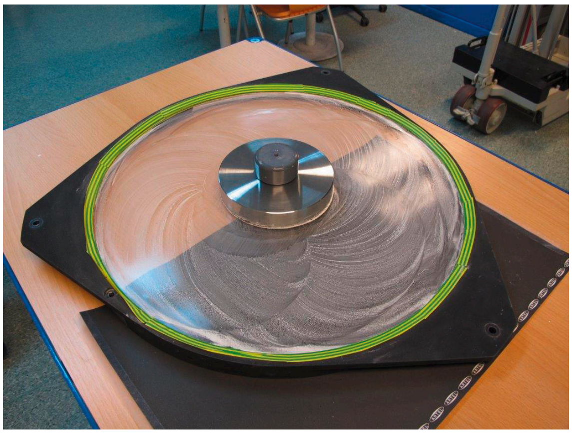


Figure 3. Photograph taken during the removal of the coating on the FORS1 LADC prisms.

Exchanging the LADC prisms

The MgF_2 antireflection coatings of the FORS2 longitudinal atmospheric dispersion corrector prisms have degraded since 1999, following an attempt to clean them. They show a lot of scattering (see Figure 2). Since then, the LADC prisms have been cleaned several times in order to remove dust and paint (from the flat-field screen) that had led to further degradation. This degradation could be the cause of the systematics seen in the FORS2 transit data.

A damaged coating may introduce:
- transmission loss larger than an uncoated set of prisms;
- scattering, leading to a decreased signal-to-noise ratio on any photometric measurements;
- variability in the transmission caused by a change in the humidity level.

A project was started at Paranal to address this issue. One aspect was to take advantage of the availability of spare parts from the twin instrument, FORS1, which is now decommissioned. We therefore decided to remove the coating from the prisms of the FORS1 LADC and exchange them with those previously in place in the FORS2 LADC. The removal of the damaged coating from the two prisms of the spare LADC was done by one of us (Blanchard; see Figure 3), using tools made of polyurethane and using cerium oxide (Opaline) for the polishing. The LADC prisms were then exchanged on 10 November 2014, while VLT Unit Telescope 1 (UT1) was undergoing maintenance.

A battery of tests

A set of test observations was performed according to a commissioning plan before (28–30 October 2014) and after (12–15 November 2014) the prism exchange. It is important to note that the coating of the primary mirror of UT1 had not been modified in the meantime, so that any change detected should be due only to the LADC exchange. These tests have allowed us to conclude that the exchanged prisms did not affect the image quality of the instrument and confirmed that the LADC was still efficient at correcting the atmospheric dispersion up to an airmass of 1.6. On the other hand, the uncoated prisms led to an increase in the measured zero points (Figure 4): the implied gain in throughput is 0.12 (*B* filter), 0.08 (*V*), 0.06 (*R*) and 0.05 (*I*) magnitudes. This improvement was also confirmed by measurement of spectrophotometric standard stars before and after the prism exchange. The gain of the throughput can be explained by the scattering previously introduced by the damaged antireflective coating. The shortest wavelengths are more affected by the scattering, which is exactly what we see.

We have also measured the precision in the relative transmission between two stars as a function of time. For this measurement, we observed a given field of stars over about one hour (so that the

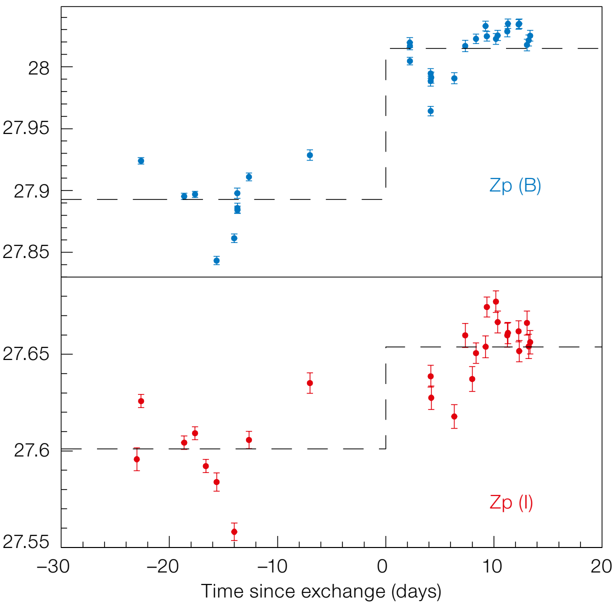


Figure 4. FORS2 zero points measured before and after the exchange of the prisms of the LADC in the *B*-band (upper) and in the *I*-band (lower). The figures clearly show the improvement in the zero points. The dashed curves indicate the mean values and highlight this improvement.

instrument rotator moved by more than 20 degrees). Observations were done in clear conditions in the *V*-band filter and the exposure time was 10 seconds. The magnitudes of some of the brightest non-saturated stars in the field were then measured for each frame, and we examined the dispersion in the light curves obtained of the stars (the sky variations were removed by subtracting the mean light curve of all stars and saturated stars were ignored). The fluxes of the selected stars were about 170 000–500 000 ADU. Sky flats were obtained close in time to the observations and the data were reduced using the ESO FORS pipeline, with SExtractor being used for the photometry.

Before the LADCs were exchanged, on the night of 28 October 2014, we monitored the field around the standard star PG0231 for 50 minutes, during which time the rotator moved about 25 degrees. The airmass of the field was 1.0. After the LADC exchange, on the night of 13 November 2014, we monitored the standard star field around NGC 2298 for 78 minutes during which time the rotator moved 47 degrees; the airmass was 1.09.

Figure 5 shows that the dispersion of the points is clearly smaller after the LADC exchange, in comparison with the earlier measurements. The standard deviation of the light curves for a star with a signal-to-noise ratio (S/N) ~ 750 decreased from 3 milli-mag before the exchange to 1.9 milli-mag after the exchange. This is, however, still larger than we expected from the white noise, so there could still be some systematics in the data. The level of systematics would, however, need to be confirmed by a more detailed analysis, as the observations of the WASP-19b transit described below seem to indicate that the level is very small.

Back in business

The fact that the dispersion of points has decreased after the LADC exchange suggests that the removal of the coating has been beneficial and the study of exoplanet transits should once again be possible. However, this could only be checked on a real case to determine the achieved precision exactly. Thus, on the night of 15–16 November 2014, we observed the transit of WASP-19b between 2014-11-16 05:16 UT and 08:49 UT (Prog. ID: 60.A-9203(F); data publicly available in the ESO Science Archive) under thin cirrus, and with the LADC parked and in simulation, as is usually done for such observations. WASP-19b was chosen as previous observations with FORS2

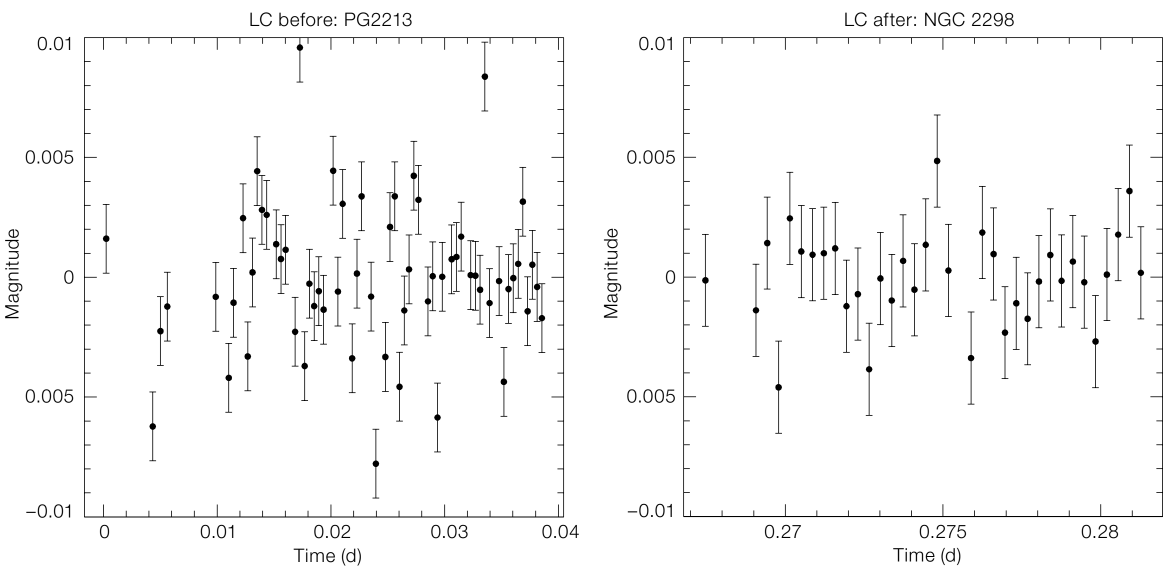


Figure 5. Light curves in the *V*-band for a relatively bright star with an S/N ~ 750 obtained before (left) and after (right) the LADC prisms were exchanged.

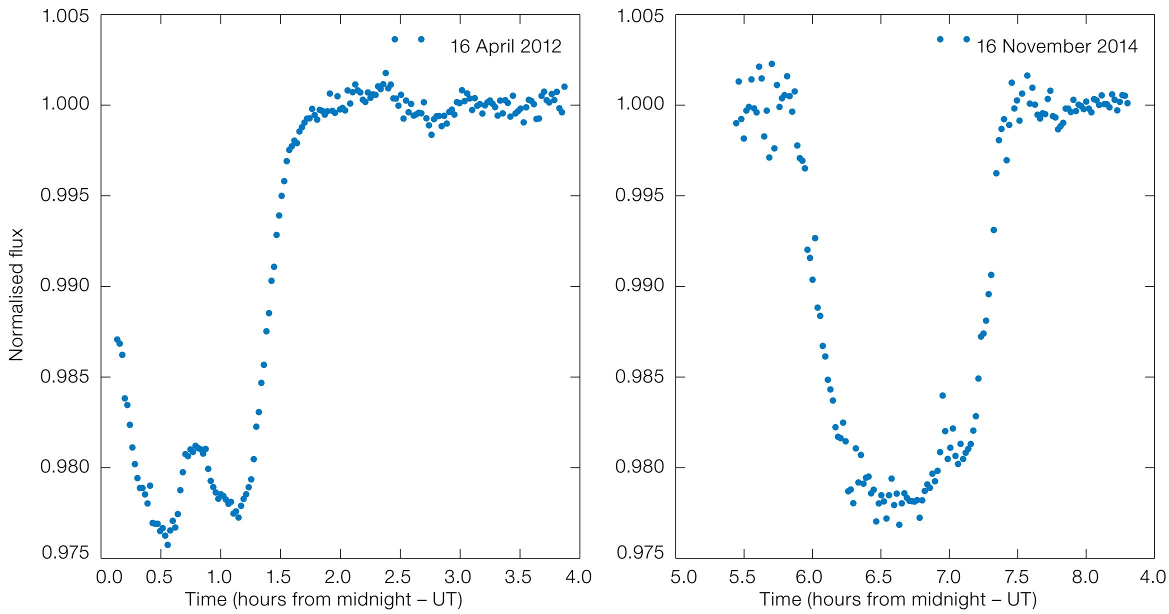


Figure 6. Light curve of WASP-19 obtained in April 2012, i.e., before the LADC prism exchange (left) and in November 2014, after the exchange (right), using the 600RI grism and integrating the spectra over the full wavelength domain ("white light"). Large systematics in the middle of the transit in 2012 are clearly visible.

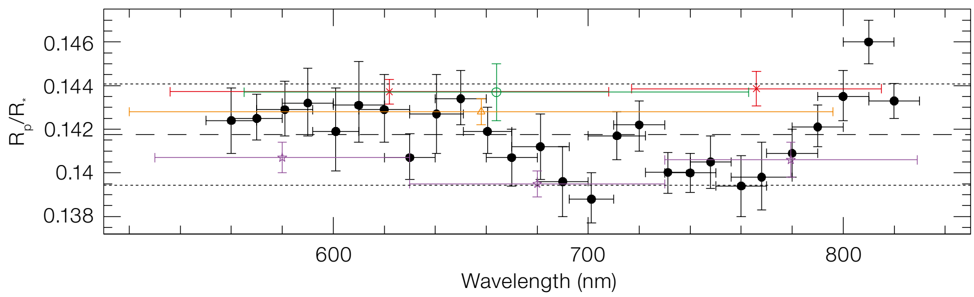


Figure 7. Transmission spectrum of WASP-19b based on our FORS2 data (with grism 600RI and 20 nm bin) from November 2014 (black, filled dots), compared to values from the literature (coloured points). The vertical error bars represent the errors in the fractional radius determination, while the horizontal bars are the FWHM of the passbands used. Note the high spectral resolution of the FORS2 data, compared to what has been available up until now. The dashed line represents the weighted mean, and the dotted lines the interval of plus and minus three scale heights.

existed (taken on 16 April 2012), thus allowing a direct comparison, while the transit duration of WASP-19b is also very short (1h 32m) and it is thus possible to cover it without expending too much observing time. Observations were done with the MXU, with 10-arcsecond-wide slits placed on several comparison stars, in the same configuration as for the 2012 observations. The grism 600RI (with the order sorting filter GG435) was used and the data were binned to a final 20 nm resolution.

The observations from 2012 reveal light curves with quite complex systematics (especially in the middle of the transit) that could not be removed even with high-order polynomial or extinction correction functions (see Figure 6). On the other hand, the new observations, performed after the exchange, show much smoother light curves, which can be detrended using a second-order polynomial. The final, detrended light curve can be modelled, providing the parameters of the transit with good accuracy. The post-egress out-of-transit residuals in the light curve are 760 μmag, very close to the value we expect from photon noise alone. This seems to indicate that the systematics that affected FORS2 have been significantly reduced.

The comparison of the planetary radius as a function of wavelength (the transmission spectrum) that we obtain with the new data and those from the literature is shown in Figure 7, highlighting the excellent agreement (see Sedaghati et al. [2015] for a more detailed analysis). The error bars of the dataset (due to the poor observing conditions and lack of suitable reference stars) do not allow us to distinguish yet between different models of the planetary atmosphere. Nevertheless, these data represent the highest spectral-resolution transmission spectrum of WASP-19b and show the new potential of FORS2 in the study of the atmosphere of exoplanets. We hope this is thus the beginning of a new era for FORS2.

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