High Accuracy Measurements of the MegaPrime Legacy Filters

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Preprint online version: September 25, 2017

ABSTRACT

We report on an ongoing effort to re-measure the transmission of the original MegaCam *ugriz* filters (now decommissioned). This effort was triggered by the discovery of inconsistencies between MegaCam observations and what we predict from the transmission curves provided by the filter manufacturers. Such inconsistencies have been spotted in the internal analysis of the CFHT-LS calibration data as well as detailed comparisons with external data-sets such as Pan-Starrs and SDSS, and are most likely due to errors in the passband models we currently use. These errors substantially degrade the constraining power of the yet unequalled spectro-photometric sample of supernovae gathered by the SNLS. For the publication of the final SNLS cosmology papers, it is essential to remeasure the legacy MegaPrime filters. This work will also significantly increase the legacy value of the CFHT-LS dataset, and more generally, of the CFHT archive.

The measurements are carried out on a dedicated optical bench, assembled at Laboratoire des Matériaux Avancés (LMA) in Lyon. They consist in a determination of the filter transmissions as a function of (1) location on filter surface (on a 27×27 grid) (2) incidence angle (3) environmental conditions such as temperature and hygrometry. Systematic searches for leaks are also performed on each filter.

We describe our final measurements of the *r*-band filter. We demonstrate that our technique delivers sub-nanometer accuracy on the effective transmission of the filter, unveiling the full legacy potential of the CFHT archive. We show that the filter spatial non-uniformities do not follow exactly a radial pattern, as was assumed in our previous analyses. We show hints for a variation of the *r* passband as a function of temperature. Finally, we discuss our plans to complete a full remeasurement of the filters CFHT has entrusted to us.

1. Introduction

Since the beginning of its operation in February 2003, the MegaPrime instrument was equipped with a set of five *sloan*-like *ugriz* interference filters manufactured by Safran REOSC. A replacement for the *i* band filter, manufactured by BARR, took the place of the original *i* filter after its accidental breaking in June 2007. The CFHT decommissioned this set of filters after their replacement by larger and sharper Materion filters in February 2015. Along their twelve years of operation, the filters were used for the acquisition of about 175,000 images totaling 9800 hours of integration time.

A number of science topics require precise knowledge of the filter transmission to make best use of this impressive legacy. Particularly stringent requirements arise from the establishment of the Hubble diagram of type Ia supernovae. The constraining power of a supernova survey strongly degrades if the average supernova fluxes in the different bands cannot be compared with a precision matching the statistical precision of the flux average in each band. With around 500 supernovae measured with $\sim 15\%$ accuracy, the large supernova survey conducted at CFHT, the Supernova Legacy Survey (SNLS), requires the calibration accuracy of fluxes in each band to be better than 5 mmag. As the calibration process involves flux comparisons of objects with substantial differences in color – of the order of 1 mag – this calibration requirement translates into a requirement in the knowledge of the filter transmission: better than 0.5 nm for filters of ~ 100 nm width. Even more direct links can be drawn between transmission knowledge and other scientific measurements such as photometric redshifts, although, in general the requirements will concern the spatial homogeneity rather than the absolute position of the transmission.

Given the cost of gathering a large supernova statistics, substantial efforts to bring the survey image calibration on par with its statistical power have accompanied the SNLS (Regnault et al. 2009; Betoule et al. 2013). While improved understanding of the instrument resulted from these efforts, an increasing set of inconsistencies between on sky data and predictions made from the transmission curves provided by the filter manufacturer have been raised:

1. Internal color terms measured between the center and edges of MegaPrime focal plane in *r* band are 40% lower than what is predicted from the manufacturer transmission curves (see Betoule et al. 2013, Figure 7).
2. In 2006, a partial survey of the transmission was conducted by the CFHT technical team. The survey covered 2 positions at the edges of the filter. Once matched in resolution and position with manufacturer measurements, the red front of the *i* and *r* filters where found approximately 8 nm redder in these new measurements. In (Betoule et al. 2013), The discrepancy has been interpreted as a change in transmission occur-

ing at or before the survey begining, and manufacturer measurements were globally distorded so that they match CFHT measurements at the available positions.
3. Even after the above corrections, color terms measured between MegaPrime and SDSS measurements are discrepant at 3σ from predicted values in band r and i_2 (Betoule et al. 2013, Table 20).
4. Unpublished analysis of data obtained by the CFHT calibration program (MiniMAPC) conducted internally by the SNLS collaboration for its final release shows that the g band transmission curve is inconstitent with STIS spectrophotometry at high significance.
5. Recent measurements of color terms between Pan-Starrs and SNLS also display small disagreements, in particular in band z (Scolnic et al. 2015, Table 4)

These inconsistencies triggered an effort to obtained improved description of the MegaPrime instrument, as it was when performing the CFHT Legacy Survey, in order to extract the complete legacy of this data. The original filter set was shipped to the Laboratoire des Matériaux Avancés (LMA) in Lyon, where a dedicated measurement bench has been build to provide a detailed survey of their transmission. The facility is described in details in Sassolas et al. (in prep). In this note, we describe a subset of these measurements and detail how they can be used to provide a much improved description of the instrument used to perform the SNLS survey. We then describe a search for environmental dependence of filter transmission and discuss the corresponding uncertainty budget.

An outline of the note follows. In the next section (§2) we describe the measurement setup that was assembled at LMA. We then present (§3) the main points of our data analysis procedure. We discuss in §4 how we synthetize the effective transmissions from the filter (integrated on the MegaCam beam) from our measurements performed at several angles. In §5 we present our studies on the dependence of the transmissions with environmental parameters, such as temperature and hygrometry, and our systematic searches for off-band leakage. We discuss our plans to complete the filter survey in §6.

2. Bench measurements of filters transmission

The main dataset consists in a grid of 27×27 measurements of the transmission, with a point every centimeter. The grid spans a 26×26 cm rectangle centered on the filter physical center. The scan is performed at normal incidence with a ⌀6 mm pencil beam, feading a fast OCEAN OPTICS HR2000 spectrometer. The measurements cover the wavelength range $200 - 1100$ nm in 2048 pixels with a spectral resolution varying from the blue edge to the red edge from 0.47 to 0.42 nm.

This grid is completed with a set of slower, more precise measurements, conducted with a high-performance Perkin-Elmer L1050 spectrophotometer. The setup is used to perform measurements at normal incidence and at incidences of 5, 10 and 15 degrees with respect to the normal. They enable a precise determination of the filter blueshifting with incidence. The four measurements are repeated at 27 positions, along the median of the filter. In addition, wavelength calibration of the L1050 has been precisely checked by measuring the transmission of a calibrated dydimium cell, in place of the filter, before each of the 4 measurements, anchoring the wavelength calibration of the dataset. We delay the discussion of other complementary data, looking for measurement systematics and environmental dependance, to Sect. 5.

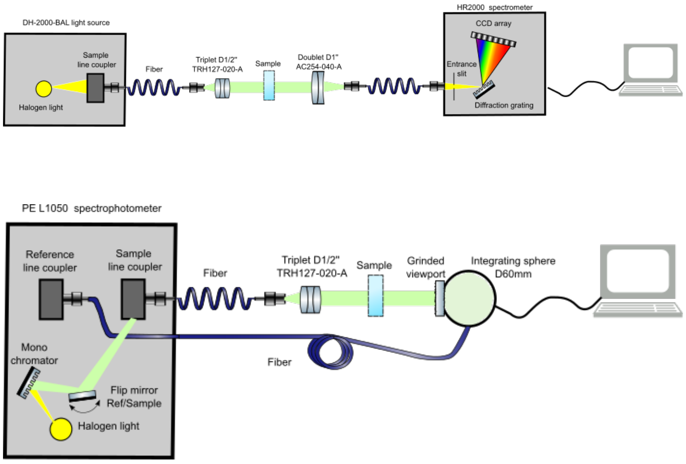

Fig. 1. *Top:* Optical setup used for fast survey of the transmission at normal incidence over the filter area (HR2000). *Bottom:* Optical setup used for detail measurement at various incidence (L1050).

The two setups are displayed schematically in Fig. 1. The first relies on the spectrometry of a white incident beam after its traversal of the filter, while the second achieves precise photometry of a monochromatic incident beam. An important difference is in the collection of the beam which, in the latter case, makes use of a large integrating sphere, and is not sensitive to misalignment effects with non-normal incidence.

3. Data analysis

Blue shift with incidence angle We fit the following model to the data:

$$T(\lambda, \theta, x, y) = T_0\left(\frac{\lambda}{\sqrt{1 - \left(\frac{\sin(\theta-\theta_0)}{n}\right)^2}}, x, y\right) \quad (1)$$

where the filter effective index n and the zero of angle measurements θ_0 are left as free parameters. The transmission at normal being a relatively smooth function of wavelength, we choose to develop T_0 on a B-spline basis with 150 nodes between 500 and 750 nm, *i.e.* one node every 1.67 nm. This simple model could be used as a good description of all measurements with non-normal incidence.

Stray light / ghosts Measurements at normal incidence, however, display enhanced transmission on edges when compared to non-normal incidence measurements as illustrated in Figure 2. We interpret this effect as light bouncing-back to the detector at wavelength where the filter is partly reflective. We account for it using a simple model of two partly reflective surfaces, one with reflectivity $1 - T(\lambda)$ and the other with constant reflectivity R, left as a free parameter. The fast grid survey (HR2000) and the slow measurements (L1050) being conducted with different setups, we allow the corresponding reflectivity coefficients to differ: R_{l1050} and R_{HR2000}. The apparent transmission in this model is

$$\hat{T}(\lambda) = T(\lambda)\sum_{i=0}^{\infty}[R(1 - T(\lambda))]^i = \frac{T(\lambda)}{1 - R(1 - T(\lambda))}. \quad (2)$$

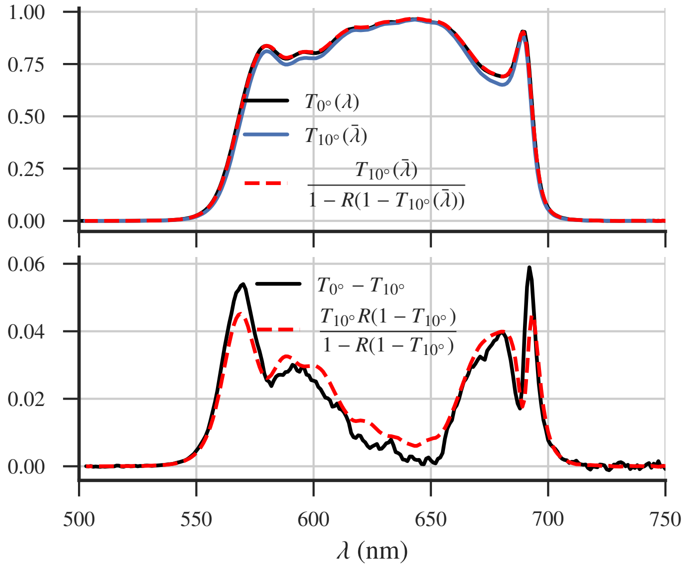

Fig. 2. *Top:* Measurement of the transmission at normal incidence (black), measurement with an incidence angle of 10° (bleue) blueshifted according to Eq. (1), and same curve corrected according to Eq. (2) for $R = 0.166$ (dashed red). *Bottom:* Difference in measurement at normal and 10° incidence (black) and transmission enhancement (dashed red) predicted by eq. (2).

Table 1. Global parameters of the filter measurement model

Filter	u_M	g_M	r_M	i_M	$i2_M$	z_M
n	-	-	1.74	-	-	-
θ_0	-	-	0.04	-	-	-
$R_{\rm hr2000}$	-	-	0.232	-	-	-
$R_{\rm hrl1050}$	-	-	0.165	-	-	-
$\delta\lambda$	-	-	1.732	-	-	-
σ	-	-	$3.79 \cdot 10^{-3}$	-	-	-

Notes. Due to its importance for cosmology, and the discrepancy between existing measurements of its passband, the r band filter was scaned in priority. Scans of the other filters are ongoing.

As visible in Fig. 2. The modified model and the measurements can now be matched at better than 1% in transmission on the entire wavelength range.

Wavelength calibration Last we align the wavelength calibration of the entire dataset on the L1050 calibration by allowing for a wavelength offset $\delta\lambda$ in the wavelength scale of the HR2000 measurements. We develop $T_0(\lambda, x_i, y_j)$ on a cubic B-spline basis with 150 nodes regularly spaced in the range $500 < \lambda < 750$, and fit simultaneously for the spline coefficients at all 27×27 positions and the parameters n, θ_0, R_{l1050}, $R_{\rm HR2000}$, and $\delta\lambda$. Best-fit parameters and standard deviation of the residuals are given in table 1.

Results To evaluate the accuracy of the resulting transmission model we compare the model prediction to the measurements, for the 27 positions where the model is constrained by 5 different sets of measurements – the HR2000 at normal incidence and the L1050 measurements at 4 different incidences. For each transmission measurement we compute a central wavelength as:

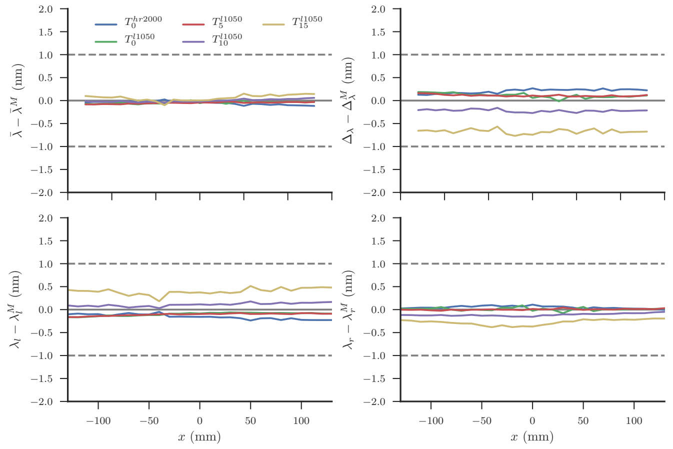

Fig. 3. Difference in central wavelength between transmission measurements and model for the 27 positions along the filter median.

$$\bar{\lambda}(\theta) = \frac{\sum_{\lambda_{i_{min}}}^{\lambda_{i_{max}}} \lambda_i T_i(\theta)}{\sum_{\lambda_{i_{min}}}^{\lambda_{i_{max}}} T_i(\theta)}, \quad (3)$$

as well as an effective filter width defined as:

$$\Delta_\lambda = 4\frac{\sum_{\lambda_{i_{min}}}^{\lambda_{i_{max}}} |\lambda_i - \bar{\lambda}| T(\lambda_i)}{\sum_{\lambda_{i_{min}}}^{\lambda_{i_{max}}} T(\lambda_i)}, \quad (4)$$

and estimates of the filter blue and red front position λ_l^{50} and λ_r^{50} as the wavelengths where the measured transmission is crossing the value 50%. Those last two estimates being noisier, we prefer to rely on integral quantity in what follows, and thus define the left and right edges as $\lambda_l = \bar{\lambda} - \frac{\Delta_\lambda}{2}$ and $\lambda_r = \bar{\lambda} + \frac{\Delta_\lambda}{2}$. The two different approach at measuring the edge positions track very similar features.

We compute the same metrics for the best-fit model prediction. The comparison is displayed in Fig. 3. After correction of the above discussed effects, the agreement of measurements with the model is everywhere better than 0.3 nm in central wavelength. The main remaining effect is an apparently different refractive index for the blue and red edges. Not accounting for this effect results in a small discrepancy between the measured and modeled width of the passband depending on the incidence angle. The passband width beeing a second order effect we did not complexify further our description.

4. Synthesis of the effective filter transmission

We interpolate the above model to predict the filter transmission at any position for a given incidence angle and thus synthesize the effective transmission as seen from a given position in the focal plane of the $f/D = 3.8$ CFHT. We have performed this computation for a simplified model of the CFHT optics, assuming a circular mirror of radius 1796 mm and focal length 13.533 m, with a circular central occultation of radius 800 mm, and filters positionned 71.5-mm away from the focal plane. We compute the integral numerically, discretizing the primary mirror on a cartesian grid with a resolution of 200 mm. We check by doubling the resolution that the numerical precision is better than 0.01 nm. It is also interesting to note that, as the beam

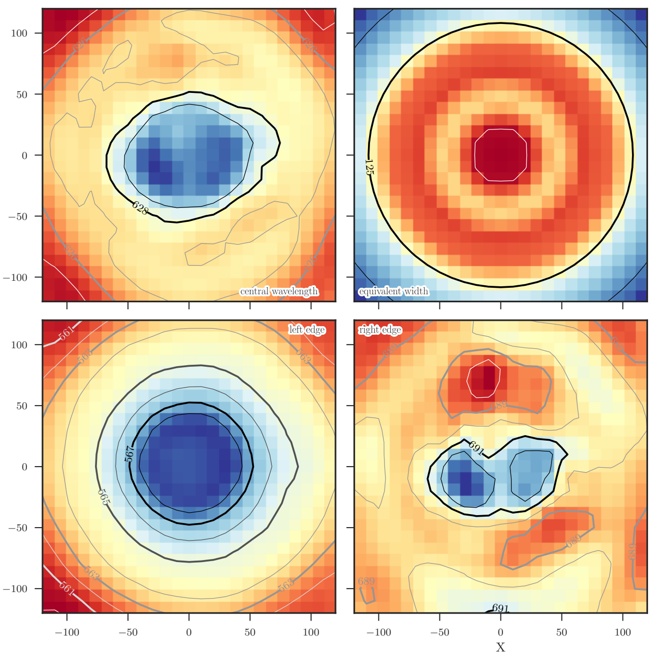

Fig. 4. Maps of the central wavelength, equivalent width and blue and red edges position for the effective transmission of the MegaCam r_M filter.

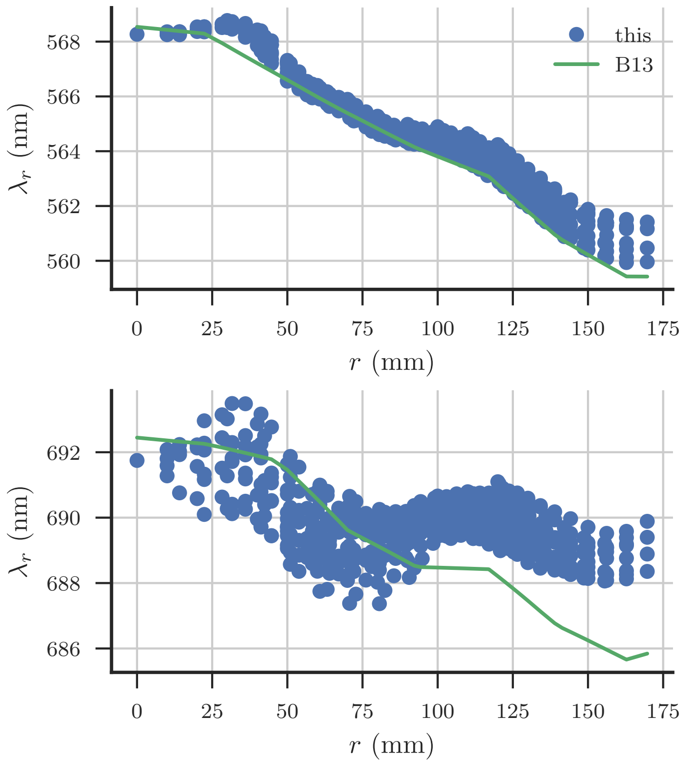

Fig. 5. *Top:* Blue edge position as a function of the distance to the filter center. The continuous green line figures the previous centrally symmetric model of the r_M filter as published in B13. The blue dots figures the present model. *Bottom:* Same for the red edge.

average the transmission over a 2 cm diameter area on the filters, the sampling of our measurements is sufficient to provide an accurate computation of the averaged transmission. The resulting synthetic transmission is summarized in term of central wavelength, equivalent width and left and right edge position in Fig. 4.

The map of the red edge shows a significant deviation from the central symmetry that was so far assumed for this filter. Comparison with our previous central-symetric model of the r filter is provided in Figure 5. The red edge evolution is significantly different at large radii, leading to differences in central wavelengths of up to 2.5 nm, with the filter being actually bluer (and more homogeneous) than previously assumed. As witnessed with the disagreement of the green curve with all our measurement points for a given radius, the discrepancy is not attributable to unfortunate measurement of a peculiar radius by the manufacturer.

Hints of this discrepancy were visible in the comparison with stellar measurements shown in Betoule et al. (2013, Fig. 7), which partly triggered this new transmission survey effort. An update of this plot including our new LMA measurement is shown in Fig. 6. The color terms are computed as linear fits to the $r-r$ versus $g-i$ color locus. The aggreement between on-sky measurements and the filter transmission model presented above is impressive. Note however, that this test only probes relative differences between filter transmission at different positions and would not be sensitive to a global error such as a wavelength calibration error or rigid shifts of the transmission with humidity and temperature.

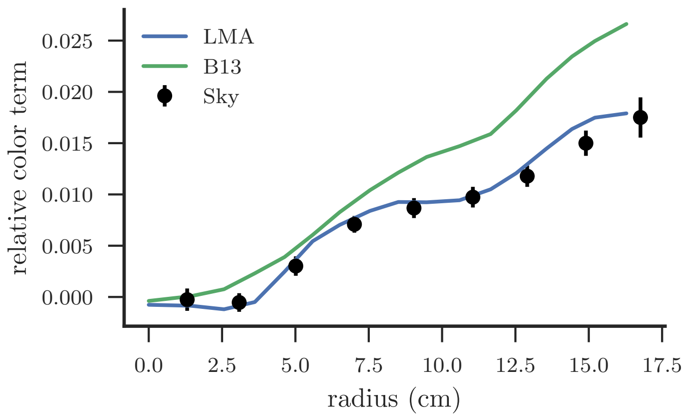

Fig. 6. Color terms between stellar measurements conducted at the center of the MegaPrime focal plane and a circular average of stellar measurements at other radiuses. This figure is an update of Figure 7 in Betoule et al. (2013). Dots figures actual on sky measurements while curves corresponds to expectations synthesized from the above model (blue) or the previously published transmission curves (green).

5. Complementary investigations

5.1. Variations of the transmission with environmental parameters

The LMA team has carried out a specific hardware development to vary the temperature and, to some extent, the humidity of their measurement enclosure. Figure 7 shows the variation of the position of the left and right edges during a continuous measurement at a fix position while the temperature of the enclosure is varied. The relative humidity also changes slightly as a consequence of the action of the cooler. Noise contribution to the edge measurement is of the order of 0.01 nm. In addition to the measured values, the result of a linear regression against temperature only, and of a simultaneous regression against temperature and relative humidity are also displayed.

The main conclusion is a clear dependency of transmission with temperature as illustrated in Fig. 7. The measured slope of the temperature-position relation are $1.41 \pm 0.05 \cdot 10^{-2}$ nm/°C for the right edge and $2.64 \pm 0.03 \cdot 10^{-2}$ nm/°C for the right edge. There are also hints for variation of the transmission with humidity although less significative: non zero slopes are measured at 5 and 8σ for the left and right edges respectively.

Efforts are currently conducted to disentangle temperature and humidity effects. This is required to enable safe extrapolation of the lab measurements to the specific observation conditions of the dry MegaPrime enclosure at the Mauna Kea summit. Not doing so would introduce an environmental systematics of the order of 0.5 nm, higher than other source of uncertainties in the presented measurement.

5.2. Off-band leakage

Integration time in the optical setup based on the L1050 spectrophotometer can be increased to large values allowing to reach remarkable sensitivity, close to 10^{-4} on a large part of the band. This enabled a search for leaks in the rejection band of filters. This search was conducted every 2 nm in the range $350 < \lambda < 1100$ nm for 1 filter position and confirmed the absence of significant leak in the rejection band of the *r*-band filter.

6. Conclusion and plans

We presented a preliminary analysis of measurements that are part of an ongoing survey of the MegaPrime filters conducted at the Laboratoire des Matériaux Avancés in Lyon. The measurement hardware and survey design have been tested in priority on the *r* band filter, due to its importance in cosmological analyses, and the survey is now complete. The survey of the *i* band filter is ongoing.

The dataset is redundant and its internal consistency is everywhere better than 0.3 nm in central wavelength. Absolute wavelength calibration of the measurement has been checked using a laboratory standard and is better than 0.3 nm. We showed that the gathered data enable accurate synthesis of the average filter transmission in the CFHT beam, and that the new data drastically improve consistency with on-sky data. Our investigations also revealed clear dependency of the filter transmission with environmental parameters which have been so far overlooked.

Reaching the accuracy required by modern cosmological analyses is harder than anticipated due to the complexity of the interference filters behavior, in particular its non-trivial change with incidence angle and temperature, and lengthy extensions of the original set of measurement are actually required to make sense of the normal incidence scans. Based on the integration time measured for the *r* band filter we estimate that gathering an equivalent dataset for the 4 remaining filters would require a minimum of 6 weeks of continuous operation of the LMA facility, split as follows:

1. Spatial survey at normal incidence: 1 day per filter
2. Measurements at oblique incidence: 3 days per filter

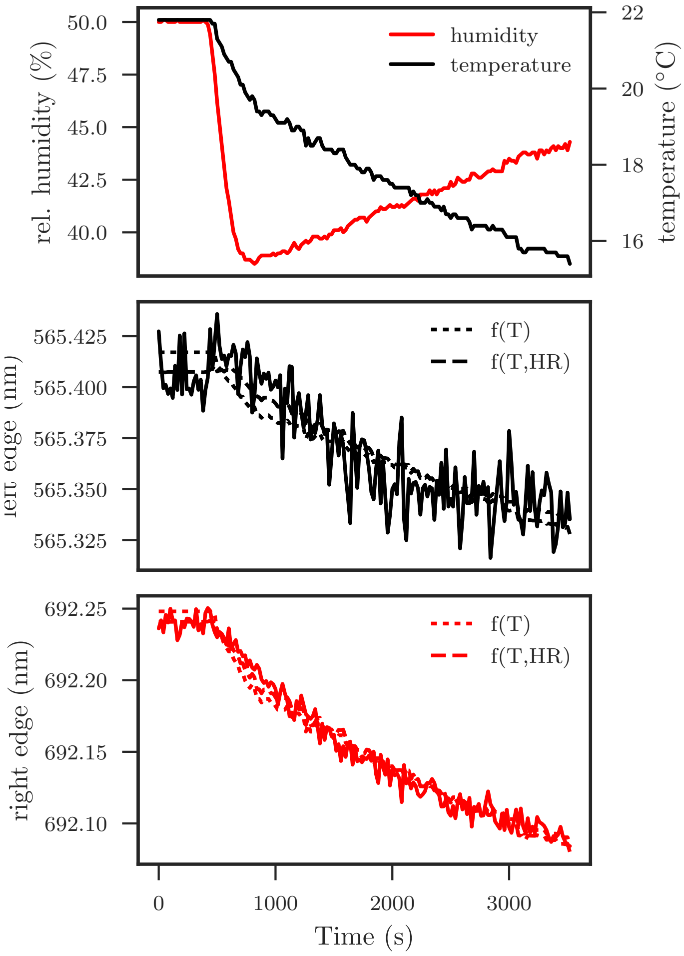

Fig. 7. *Top* Measurement of the air temperature and relative humidity in the bench enclosure over the course of a 1 hour continuous monitoring of the *r* filter transmission. *Middle/Bottom* Variation of the left/right edge position with time (plain line). The noise in the measurement is of the order of 0.01 nm. A single $> 5\sigma$ discrepant point has been removed from the sequence. Also shown are the prediction from a linear regression against temperature (dotted line) and the prediction from the bilinear regression against temperature and humidity (dashed line). In both cases the preference for the second model is statistically strong $\Delta\chi^2 = -31$ and -61.

3. Measurements at varying temperature: 1 day per filter
4. Search for leaks: 2 days per filter.

However, the workload of the measurement bench is incompatible with continuous operation as it is shared with other important objectives (in particular the production and test of optical elements for the Subaru Prime Focus Spectrograph). In practice, only a third of the time can be devoted to the filter measurements increasing to 4 months the actual time required to complete the survey. Meeting the current deadline for filter reimportation would require to stop the ongoing investigations of environmental dependencies and drop measurements that are crucial to model the filter transmission. Given the size of the trends observed so far, we believe that poor understanding of the environmental effects and incomplete measurements would present a high risk of spoiling the effort made to gather a high-accuracy survey by preventing accurate extrapolation of the survey results to the specific CFHT beam and weather conditions of the Mauna Kea summit. In consequence we would like to ask for a *6 months extension of the exportation duration*, allowing to complete the survey and leaving a two months security margin that could be devoted to additional measurements associated with environmental effects.

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