COATEST 7L

Application Note #8

Absolute values of reflectivity measurements

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Introduction

This note discusses how “absolute” values of the reflectivity of a coated mirror are obtained.

For most work, relative measurements seem sufficient in order to monitor the degradation of the coating with exposure and decide when to clean it or replace it. But this situation is not satisfactory for two reasons:

1- Each observatory develops its own standard and lives with it; inter-comparisons are difficult because there is no standard. The situation is similar to the one prevailing in Middle Age with units: a five league distance was not the same if the league was ‘imperial’ or ‘spanish’ or ‘french’!
2- In the same observatory, if the reference drifts, all measurements are drifting without any means to recognize it.

This is why absolute measurements are justified and we give, in this note, the way of achieving it.

Structure of a "reflectometer"

It is important to know that an apparatus called "reflectometer" hardly deserves this name because it does not actually "measure" the reflectivity of a sample mirror, but, more modestly, compares the reflectivity of the sample mirror to the reflectivity of a gauge or reference mirror. The complete measurement "assumes" that the reflectivity of the gauge is known by an independent experiment.

Precisely, the reflectometer tells:" if the gauge has a reflectivity of 87.5% at that wavelength, then the sample mirror has a reflectivity of 88.8%"

The final answer can be wrong for two reasons:
The reflectivity of the gauge is not actually 87.5% but 86.3% or any other value.
The measurement of the reflectometer does not repeat from one measurement to the other so that if you were to repeat the complete measurement (gauge then sample) several times, you would get different answers : 87.5%; 87.9%, 86.8% 87.2% …

Here, one should at once notice another difficulty of such comparison. The reflectivity of coated mirrors varies with the position of the measuring spot on the mirror. This variation is an indication of poor coating and can reach values of several percents. So that if you perform the last experiment, you do not know whether the reflectometer has a poor repeatability or whether the mirror has a poor coating. The only way to test the repeatability of a reflectometer is the perform series of measurements without moving the reflectometer on the test mirror.

The absolute reflectivity of a sample mirror can be obtained in two steps:
Measure the absolute reflectivity of a dedicated gauge or reference mirror
Compare the reflectivity of the sample mirror with the reflectivity of the gauge, using an apparatus called 'reflectometer' that has two essential properties: -it is stable and repeatable; - it is linear in the region where it is used (for instance better than 0.1% between 50% and 100% reflectivity for a mirror reflectometer.

One could ask why the technique for measuring the absolute reflectivity of the gauge cannot be directly utilized to measure the sample mirror. The reason is that one wishes to be able to measure any 'sample mirror': flat, curved, large, small; and sometimes in acrobatic positions. While the absolute measurement of the gauge requires very special conditions mainly on the size of the gauge.

We turn to the description of this system of absolute measurement.

The comparison reflectometer

Fig. 1 shows the essential structure of the Comparison reflectometer. The light source is a Led or a combination of Leds if several wavelength bands are required. After proper baffling (not represented), the central beam is splitted by an uncoated thin sheet of glass (BS). The reflected beam is directed onto the reference detector Dr through the stop Sr. The transmitted beam is directed through a well baffled collimator (ColSource) to the sample mirror and reflected back to the detector collimator. At the focus of the lens; a stop (Ss) defines the acceptance angle of the reflectometer by suppressing the scattered light at an angle larger than atan(r/f) where r is the radius of the stop and f the focal length of the lens. The detector Ds picks up the reflected beam.
The two detectors are identical as well as the front end electronics. The latter is composed of a trans-impedance amplifier and an A/D converter. Finally the digital signal s is divided by the reference signal r and multiplied by the calibration factor **cal** to obtain the reflectivity:

$$R = cal * s / r \qquad (1)$$

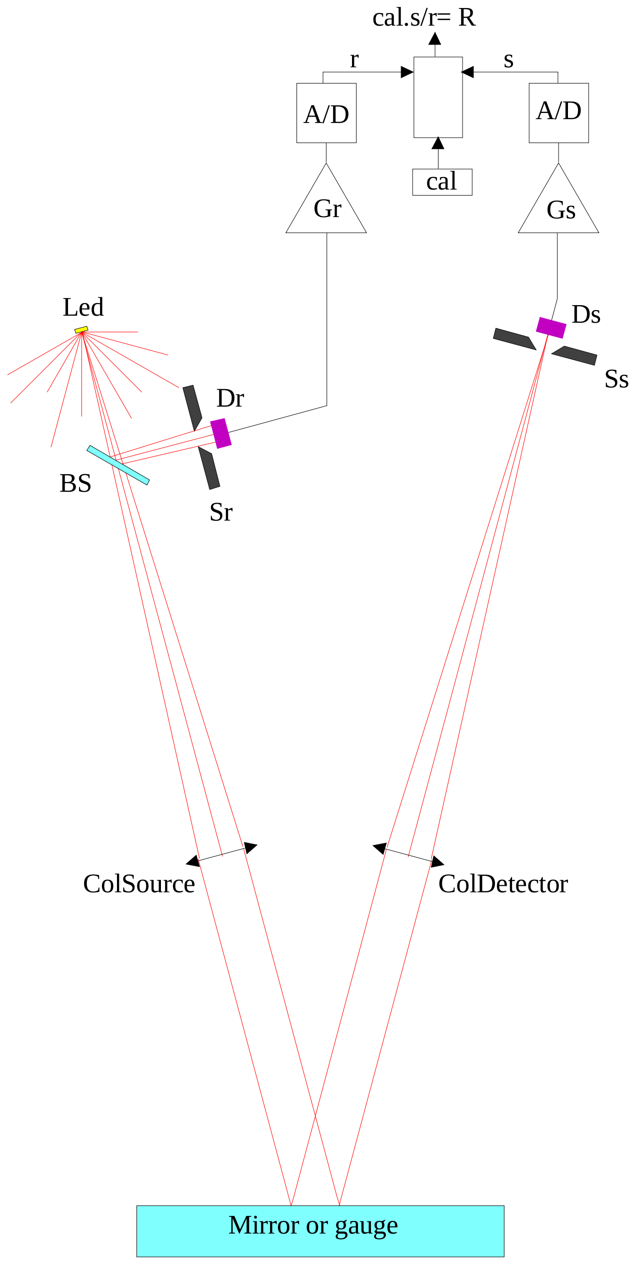


Fig. 1 Principle of a comparison reflectometer.

The calibration factor is obtained by measuring a gauge that has a known reflectivity Rg giving the measurement result: $Rg=cal*s_g/r_g$ from equ (1) and hence $cal=Rg*r_g/s_g$.

The stability of the comparator requires that (Ds*Gs)/(Dr*Gr)= constant.
This condition can be fulfilled with great accuracy.

Note that for clarity, the angles are shown larger than actual (8°).

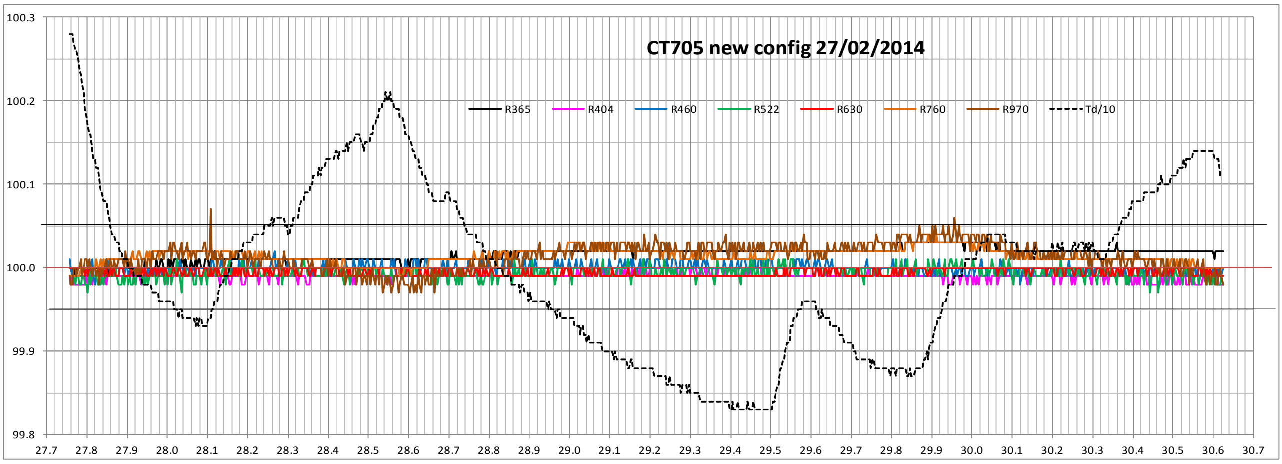


Fig. 2 Repeatability and stability of CT7 reflectometer

Fig.2 show a recording of reflectivity measurements in seven channels obtained with the new configuration of the CT7. It represents measurements every 5 min during 69 hours. All channels were calibrated at 100% for ease of reading the results on the same scale; the temperature in °C has been divided by 10 and brought around 100 by adding a constant.

One sees that the repeatability, i.e. the variation from one measurement to the next is better than 0.01% except for the 970 nm channel. The three day stability is much better than 0.05% for a temperature variation of 4.5°C.

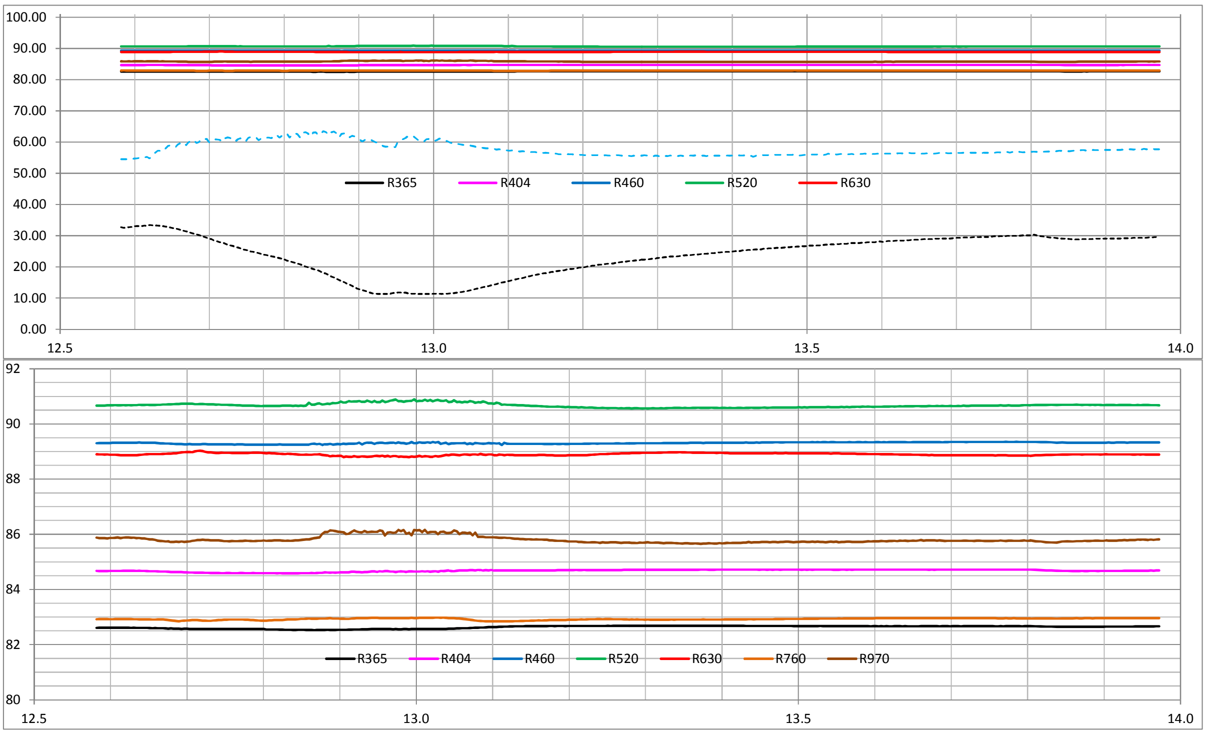
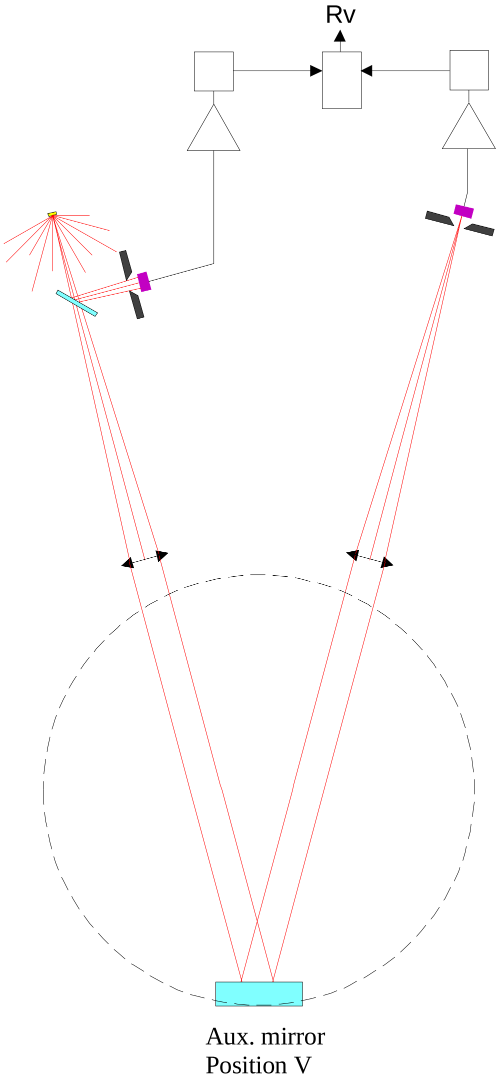


Fig. 3. Recording of the actual reflectance with CT707.

The lower diagram in Fig. 3. is the ordinate expansion of the upper one. One sees that over 34 hours and a temperature variation of 32°C, the stability is better than +/-0.2% for the 520 and 970 nm channels, and better than +/-0.1% for the five others.

The absolute calibration

We now turn to the description of the absolute measurement of the reflectivity Rg of the gauge. This is done in a dedicated instrument using a technique due to Strong and commonly called VW technique; it will soon be clear why. Fig. 4a and 4b show the structure and operation of the VW measurement.



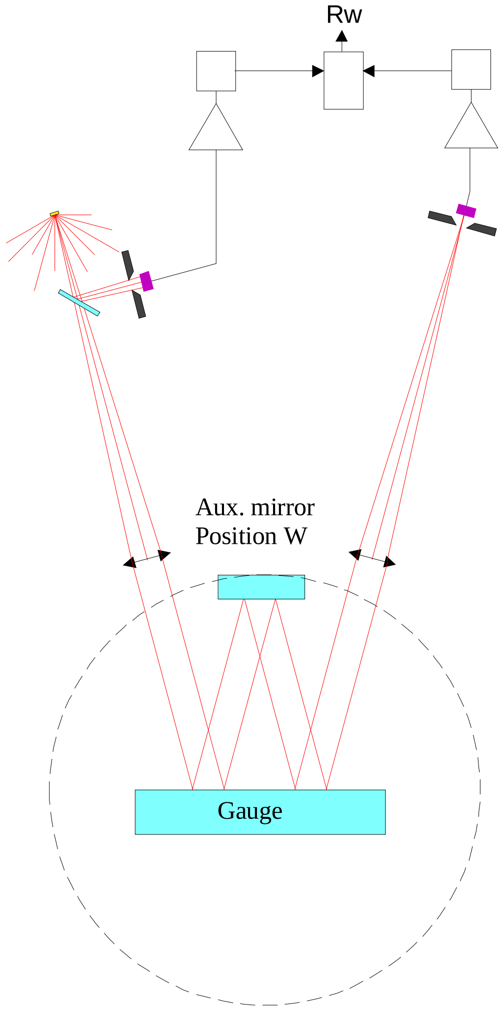


Fig. 4a The V configuration without the gauge

Fig. 4b The W configuration with the gauge

The operations are the following: An auxiliary mirror (Aux. mirror) is mounted on a rotation table with two preset fixed positions at 180° from each other; the lower position (V) and the upper one (W).
On top of the instrument, one recognizes the elements of the reflectometer which are permanently fixed to the VW jig.
The measurement in Position V yields a reflectivity measurement **Rv**.
The auxiliary mirror being turned in the upper position, the unknown gauge is introduced so that its reflecting surface is parallel to the auxiliary mirror and contains the rotation axis thereof.
A second measurement in this W configuration yields a reflectivity measurement **Rw**.
Now observe that the path of the beam in this second measurement is exactly the same as it is in the first one except that the beam is reflected twice on the gauge. It follows immediately that the ratio between the second measure and the first one is equal to the square of the gauge reflectivity, independently from the unknown reflectivity of the auxiliary mirror.

Hence **Rg = sqrt(Rw/Rv)**

A thorough study of the errors due to small misalignments shows that it is easy to obtain a very accurate setting and, if the repeatability of the measuring part, i.e. of the CT7 is excellent, the absolute accuracy obtained is comprised between 0.1% and 0.5%.

It must be noticed however that the VW jig uses two areas of the gauge symmetric with respect to the centre, while the CT7 uses the central part of the gauge. It is then mandatory that the gauge be of high quality concerning the uniformity of the coating. The error there should not exceed 0.05%, as long as the gauge remains clean and unscratched.

The instrument does not need to be calibrated but it is practical to run a calibration in the V configuration, setting all the calibration reference to 100%. Then measuring in the W configuration yields the simpler result:

Rg= sqrt(Rw)

Tables 1a and 1b.

R365	R404	R460	R522	R630	R760	R970
82.64%	84.65%	89.29%	90.65%	88.95%	82.96%	85.89%
82.64%	84.66%	89.30%	90.68%	89.00%	82.98%	85.92%
82.62%	84.67%	89.30%	90.68%	88.98%	82.97%	85.91%
82.64%	84.68%	89.30%	90.68%	88.99%	82.99%	85.91%
82.57%	84.64%	89.29%	90.65%	88.80%	82.86%	85.84%
82.54%	84.65%	89.29%	90.66%	88.80%	82.86%	85.83%
82.68%	84.33%	89.13%	90.50%	89.01%	82.98%	85.81%
82.61%	84.87%	89.41%	90.76%	88.80%	82.86%	85.89%
82.66%	84.87%	89.42%	90.74%	89.00%	83.00%	85.93%
82.53%	84.65%	89.29%	90.67%	88.71%	82.78%	85.83%
82.61%	**84.67%**	**89.30%**	**90.67%**	**88.90%**	**82.92%**	**85.88%**
0.04%	**0.08%**	**0.04%**	**0.04%**	**0.10%**	**0.07%**	**0.04%**

R365	R404	R460	R522	R630	R760	R970
82.61%	84.67%	89.26%	90.66%	88.98%	82.93%	85.89%
82.56%	84.69%	89.22%	90.74%	88.92%	82.85%	85.85%
82.54%	84.69%	89.24%	90.72%	88.97%	82.89%	85.87%
82.54%	84.63%	89.24%	90.64%	88.92%	82.84%	85.87%
82.54%	84.64%	89.25%	90.67%	88.95%	82.89%	85.87%
82.52%	84.65%	89.28%	90.62%	89.02%	82.94%	85.90%
82.54%	84.62%	89.24%	90.66%	88.94%	82.82%	85.85%
82.62%	84.77%	89.23%	90.86%	88.90%	82.84%	85.81%
82.57%	84.71%	89.26%	90.80%	88.96%	82.89%	85.86%
82.55%	84.65%	89.30%	90.62%	89.02%	82.96%	85.90%
82.56%	**84.67%**	**89.25%**	**90.70%**	**88.96%**	**82.89%**	**85.87%**
0.03%	**0.03%**	**0.02%**	**0.06%**	**0.03%**	**0.04%**	**0.02%**

The two tables show two series of 10 measurements made with the calibrator on the gauge G1407. The last two lines are the average and RMS deviation of the ten measurements.

One sees that the global absolute accuracy is in the range of +/-.05% on all channels.

Note, however, that one records, on the same G1407, reflectance gradients three times as large (0.15%) over an area of 1 square cm.

Other way of obtaining the absolute value of Rg

Usually, the gauge or reference mirror is measured in a separate laboratory. The most often used method is similar to the VW method described here above.
The source is a spectrograph such as a CaryV with a special fixture reproducing the VW configuration (Fig. 5).

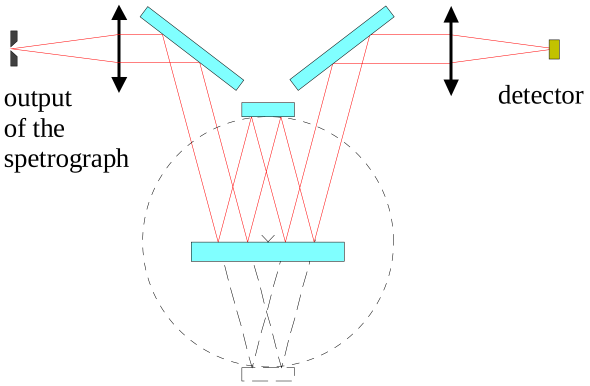


Fig. 5 Absolute calibration attachment.

This configuration does not give an absolute accuracy better than 2% because one has to run through the spectrum first in configuration V and then in configuration W, then make the ratio between the two recordings; the time elapsed between the two measurements is therefore 50 to 100 times larger than with the CT7. The method of measurement does not allow reaching a repeatability approaching the 0.01% of the CT7.

Another drawback is that the angles of the bundle with the gauge is usually much greater than 8° so that the method is prone to be sensitive to polarization and to interferometric effects if the mirror is coated for protection. The large angles result in a larger distance of the two spots on the gauge so that it must be large and very uniform.
Finally, one obtains the monochromatic reflectivity, and in order to use the gauge for calibrating a handy reflectometer, one must convolute the reflectivity with the band intensity of the reflectometer source. The latter is usually a LED and one cannot use the 'effective' wavelength of the latter instead of the convolution when one wants to reach an overall accuracy of 0.5%.

All these error contributors are drastically reduced in the method we have proposed in the first part of this note:

- Measurements in the two configurations are done within less than one minute with an instrument showing stability of the order of 0.02% per hour.
- The same beam and the same source are used in measuring the absolute reflectivity of the gauge and calibrating the reflectometer with the gauge.
- The used part of the gauge is quite small and easily made and maintained uniform.
- The angle of incidence is 8° on both the absolute calibration jig and the reflectometer so that one has not to take care of problems due to polarization or to thin layer interferometric effects.

Fig. 6. Zemax ray tracing of the calibrator.

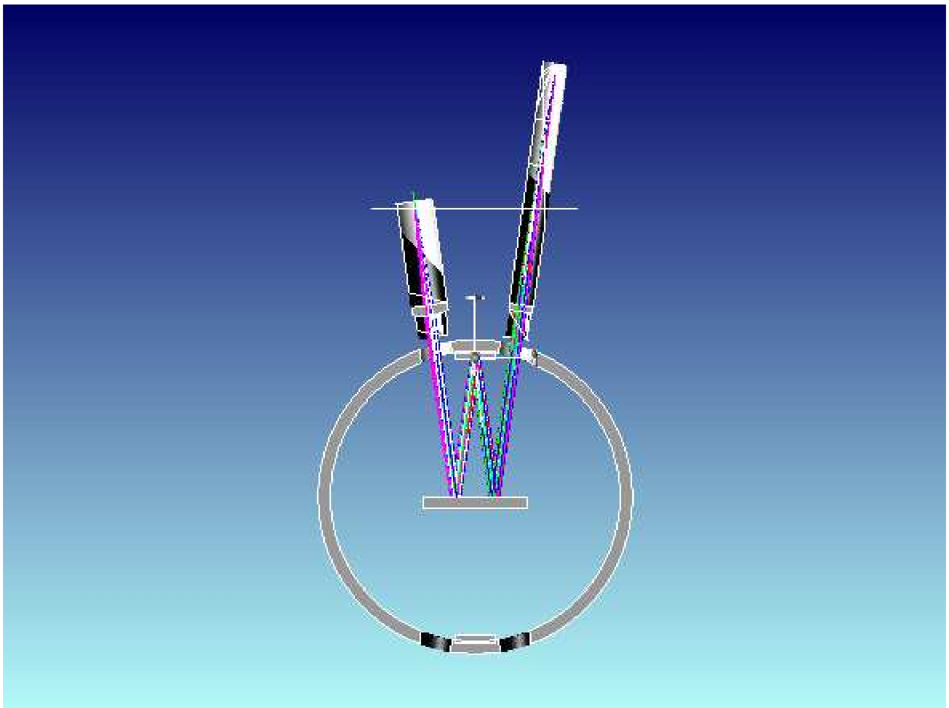


Fig. 7. Cut of the preceeding