Quality control for multi-detector instruments: a test bed with VIMOS

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ABSTRACT

The performance of all scientific instruments of the Very Large Telescope (VLT) is monitored by the Quality Control (QC) Group of the European Southern Observatory. Basic goals are to detect instrumental failures on a short time basis and to evaluate and detect long-term trends. The QC process mainly involves pipeline-produced calibration products and is set up on a file by file basis. This implies that currently each detector or channel of an instrument is checked separately. All operational VLT instruments have a low number of detectors but with the advent of multi-detector instruments like OmegaCAM and VISTA, which have up to 32 individual detectors, this approach becomes unfeasible. In this paper, we present solutions for this problem for the VLT instrument VIMOS. With four detectors operating simultaneously, VIMOS can be regarded as a test bed for studying new QC concepts which can be implemented for other instruments with higher multiplicity.

Keywords: quality control, VIMOS, instrument performance, multi-detector instruments

1. INTRODUCTION

1.1. Quality Control on VLT Data

The European Southern Observatory operates on Cerro Paranal in Chile the four unit telescopes of the VLT, currently including nine scientific instruments mounted on different foci, and the VLT Interferometer (VLTI). Two further telescopes dedicated to surveys in the optical and infrared spectral regions will be operational soon: the VLT Survey Telescope[1] (VST) and the Visible and Infrared Survey Telescope for Astronomy[2] (VISTA).

All data measured with the VLT instruments are continuously evaluated. This Quality Control process has two main parts. The first is executed on Paranal and involves visual inspection of raw calibration and science data. It also ensures that user-specified constraints for science observations like air mass and seeing limits have been fulfilled (QC level 0).

The second step is performed by the Quality Control Group at ESO headquarters in Garching. All calibration measurements are processed by data reduction pipelines. For each calibration type, a set of QC parameters (e.g. mean bias level, spectral resolution) is defined and measured. The current values for these parameters are calculated from recent calibrations and final calibration products are created. QC parameters are evaluated and compared to previous measurements and the products are inspected and certified (QC level 1). The goal is to determine the current status of the instrument, to follow the behavior of the instruments over a longer time period, and to ensure consistent data quality. Feedback to Paranal is given with respect to instumental performance and long-term trends.

A general description of VLT QC can be found in Ref. 3 and on the ESO QC web pages: www.eso.org/qc.

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Table 1. Basic calibration types for VIMOS.

calibration type	mode	description	purpose	products
bias	all	series of 5 bias frames	detector bias level	master bias
sky flat	IMG	series of 4 or more sky exposures during twilight	detector structure	master sky flat
standard star field	IMG	field of photometric standard stars for each filter	zeropoints	reduced image, zeropoints of night
MOS flat	MOS	flat lamp exposures through MOS mask and grism	pixel-to-pixel variations, blaze function	master MOS flat
MOS wave	MOS	arc lamp exposure through MOS mask and grism	wavelength solution	line table
MOS standard	MOS	spectroscopic standard star	quantum efficiency and overall response	efficiency and response curves
IFU flat	IFU	flat lamp exposures through IFU	pixel-to-pixel variations, blaze function	master IFU flat
IFU wave	IFU	arc lamp exposure through IFU	wavelength solution	line table
IFU standard	IFU	spectroscopic standard star	quantum efficiency and overall response	efficiency and response curves

1.2. VIMOS

The Visual Multi-Object Spectrograph[4] (VIMOS) consists of four identical optical arms. Each has a field of view of $7' \times 8'$ and covers one quadrant of the total field of view. Each arm is equipped with one EEV 4K × 2K CCD detector and with six different grisms of spectral resolution between 200 and 2500. VIMOS can be operated in three different modes: imaging (IMG) using UBVRIz filters, Multi-Object Spectroscopy (MOS) using masks with up to 200 slits per quadrant, and spectroscopy with an Integral Field Unit (IFU) consisting of 6400 fibers (80 × 80).

Table 1 gives an overview of the most relevant calibration types of VIMOS. The frequency of calibration measurements depends on the type. Bias frames, and IFU flat and arc lamp exposures in one dedicated setting, are measured daily in order to determine a quick check of the instrument status. Other calibration measurements are triggered at least partly by science observations. For IFU, it is mandatory to measure flat and arc lamp calibrations immediately after the science exposures because of instrument instabilities. The same procedure is also often used for MOS.

A single exposure always gives four different raw files, one for each quadrant. The pipeline procedures operate on each quadrant independently and consequently every calibration or science product has a multiplicity of four. The pipeline products are evaluated using a set of MIDAS procedures which are set up to use products from a single quadrant. A detailed description of these procedures can be found in Ref. 5. Thus, four separate QC checks are needed in order to evaluate a single calibration measurement and to certify its pipeline products.

1.3. Multi-detector Instruments

The approach to work on a file-by-file or detector-by-detector basis is common for all VLT instruments. This is feasible for a low number of detectors but with the advent of OmegaCAM (VST) and VISTA, which have up to 32 detectors, advanced QC procedures have to be developed which allow to certify more than one calibration product at once. This will be essential for day-to-day QC work with multi-detector instruments:

- Since the number of QC checks scales with the number of detectors, traditional checks will become unmanageable.
- In multi-detector instruments, trending has two dimensions: time and detector ID. The challenge is to discover coherent changes (all detectors at once) as well as single-detector outliers, and to distinguish between both types of outliers.

We have used VIMOS with its four detectors as a test bed for developing new QC concepts for higher-multiplicity instruments.

2. QUALITY CONTROL ON PRODUCT FILES

2.1. Basic Principles

It is important to note that a lot of knowledge about the instruments is extracted during the QC process but for day-to-day certification of products it is mainly important to notice sudden changes in the trending and in the products. For example, the actual level of the mean bias for the current master bias is interesting in itself but for the daily QC purpose it is more important whether the actual value is stable within the usual fluctuations.

For opimizing the VIMOS QC procdures we

- improve visualization towards displaying all detectors at once
- define reference products
- define, and follow up, mean and rms of QC parameters averaged across detectors
- utilize automatic detection of changes in the products and the QC parameters and define a scoring system for outliers.

Products are visualized so that all four quadrants can be seen simultaneously. This allows a quick overview of the complete data set.

The detection of changes is facilitated by the definition of reference products and the focus on comparison of the most recent frames to them. In the case of imaging, division of the actual product by the reference frame allows to notice changes in the two-dimensional structure or for individual lines and pixels. The evaluation is performed numerically and by visual inspection. For both cases, it is essential to properly define pixel values that are regarded as outliers. Typical variations should be disregarded in numerical searches but any significant change should be detected and should be clearly visible when images are displayed. It is also necessary to update the reference frames from time to time.

The usage of reference frames implies a reduction of information since, for example, the actual structure of a bias frame is not displayed. Only changes compared to the reference are visible.

Another area for reducing complexity can be found for trending of QC parameters if averages over all quadrants and standard deviations are used instead of individual values (see Sect.3).

In the following sections, we show an implementation of these principles for VIMOS and show the effects of automation and proper visualization.

2.2. Bias Frames

Bias frames for VIMOS are usually measured daily for both read-out modes. They typically consist of five individual frames for each of the four quadrants. The pipeline creates a master bias frame as the median of five raw frames for each quadrant and read-out mode. This results in eight master files in total. A QC plot with several panels and four images is created for each master by the traditional QC procedure. This gives in total 40 images that have to be checked for a complete set of VIMOS bias measurements.

For an overview plot that involves all four qudrants, we have condensed the information present in the above plots and images. The new bias QC procedure consists of the following steps:

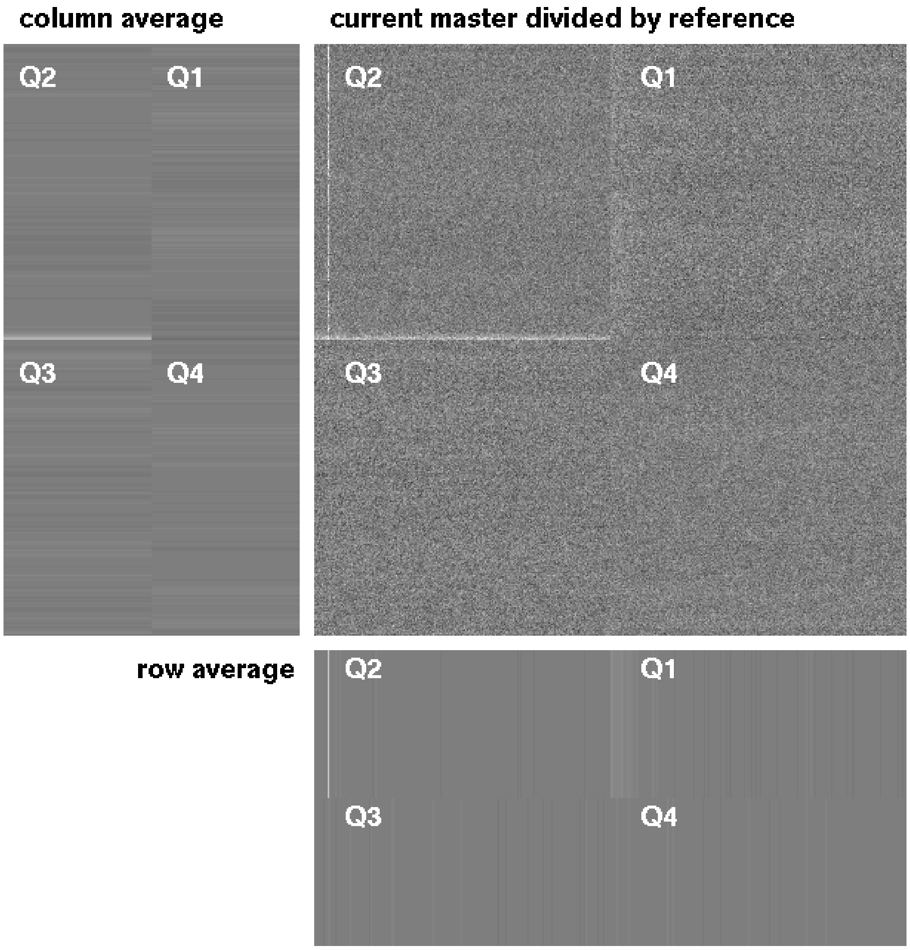

Figure 1. Example overview for improved QC on bias frames. All four quadrants (labeled Q1–Q4) are displayed simultaneously. The upper right part shows the *ratios* of the master bias and reference frames. The averages of all columns are displayed at the left, the averages of rows at the bottom, in both cases expanded to fill the second dimension for better visualization.

1. The current master bias frames are divided by reference frames.
2. From these ratios, averages over all columns and rows, respectively, are calculated.
3. The ratio and average frames for all four quadrants are shown simultanelously.
4. The ratio frames are evaluated numerically to find pixels with deviating values; the average frames are searched for bad columns.
5. Standard deviations of the raw and master frames are calculated to control the mastering process.
6. Trending for a selected set of QC parameters is shown (see Sect. 3).

For each read-out mode, four images are produced (ratio, averages of columns and rows, trending). This gives in total eight images for a complete set of VIMOS bias measurements (compared to 40 in the traditional regime).

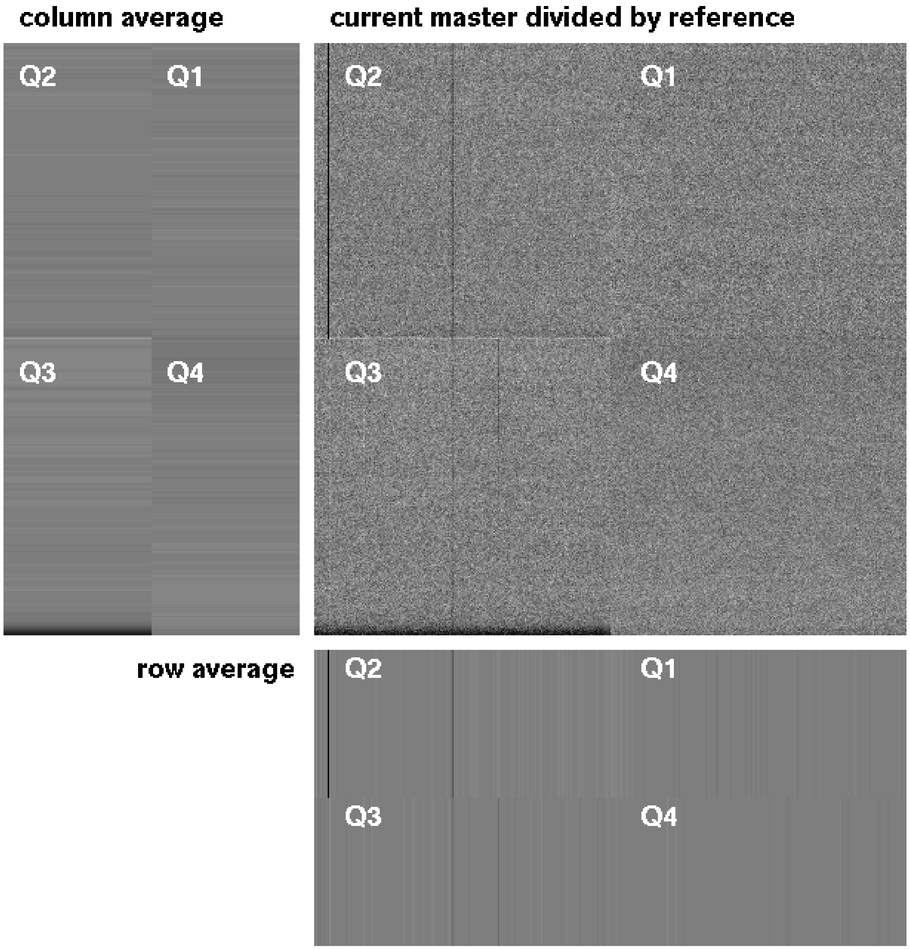

Figure 2. Example of new bias QC images after changes of detector electronics. Compared to Fig. 1, new features appeared in quadrants 2 and 3 which were not present before.

An example of the displays for the ratio and average frames for all four quadrants is shown in Fig. 1. The cuts for the gray scales have been set so that any pixels having values 0.5% above or below the average of all pixels in each sub image are displayed as white or black, respectively. These are regarded as outliers for the current test.

Using cuts of 0.5% around the average ensures that statistical variations are suppressed during visualization: most pixels in Fig. 1 are well within the limits and are displayed in shades of gray. The only outliers are found in quadrant 2 as white pixels. One column clearly has higher values than the reference. This can be seen in both the ratio image and the row average. Inspection of the unbinned frame shows that this is a single hot column that has values around 14000 ADU and typically varies by a few hundred ADUs within 24 hours. Also in quadrant 2, the lowest rows have higher values as in the reference. Inspection of images from several successive days shows that these pixels show a variation of about 1% on a timescale of 24 hours. This is a factor of two higher than the typical rms of a VIMOS master bias.

In Fig.2, we show a bias example that deviates from the typical appearance. The frames have been measured after a change in the detector electronics of quadrants 2 and 3 which caused an increase of the bias level in quadrant 2 by 10 ADU. In the two-dimensional structure of the bias, most prominent is a change of the relative level in the lowest rows in quadrant 3. These rows have been stable before. Compared to Fig. 1, a change of the

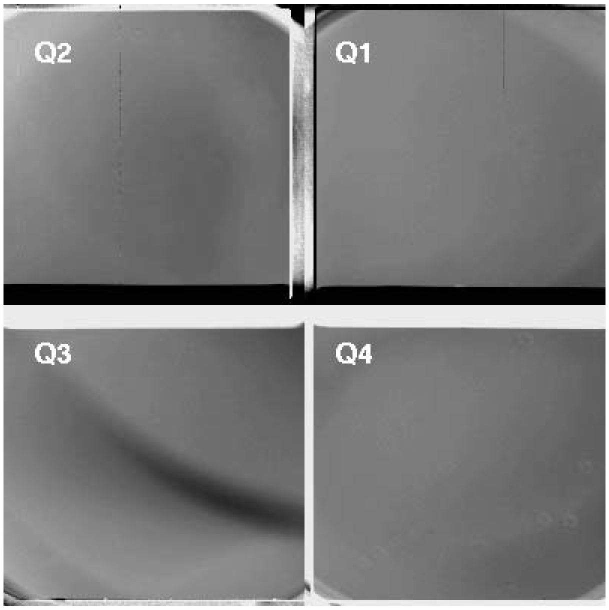

Figure 3. Example of master twilight flats of the U filter divided by reference frames.

features in qudrant 2 can be seen, too. These changes appear, however, also during normal operations and are not specific to the intervention on the electronics.

Since the images are necessarily rebinned for visualization, it can happen that outliers are interpolated and disappear from the users's display. Therefore, also the unbinned images are numerically evaluated and the results are displayed on the screen during certification. Outliers have been defined by using multiples of the typical rms of the ratio frames as starting points and have been fine-tuned in the course of these tests.

2.3. Flat Fields for Imaging

Quality Control on flat fields for imaging has some similarities to bias QC. We focus here on VIMOS twilight flats. In both cases, the average level, noise and statistical parameters, and the two-dimensional structure have to be monitored. Therefore, the procedures developed for the bias frames can, in principle, also be used for flat fields. The main difference is due to the fact that VIMOS twilight flats are not well illuminated at the edges and show strong variations there. These regions have to be masked for evaluation and statistics.

Fig. 3 shows an example of ratio images for all four quadrants. The deviations near the borders of the quadrants are the most prominent features. Some additional structures are also present, especially in quadrant 3.

VIMOS twilight flats typically have large-scale gradients of about ±5% compared to the average of the flat. Due to the division by a reference, these gradients are cancelled out in Fig.3. The remaining structure in quadrant 3 is due to a variation of the order of 0.5% from day to day which affects flat-fielding of science frames. As long as the variation is smaller than the global gradient, flat-fielding is still useful. The strength of this effect is monitored as shown in Fig.3.

3. NEW CONCEPTS FOR TRENDING OF QC PARAMETERS

3.1. Scoring

Scoring is the automated comparison of QC parameters for a new data product with those of existing products. For instance, the read noise value measured in a new master bias is compared to the mean value over the last two months. In its simplest form, scoring comes as outlier detection. If the new value deviates by more than,

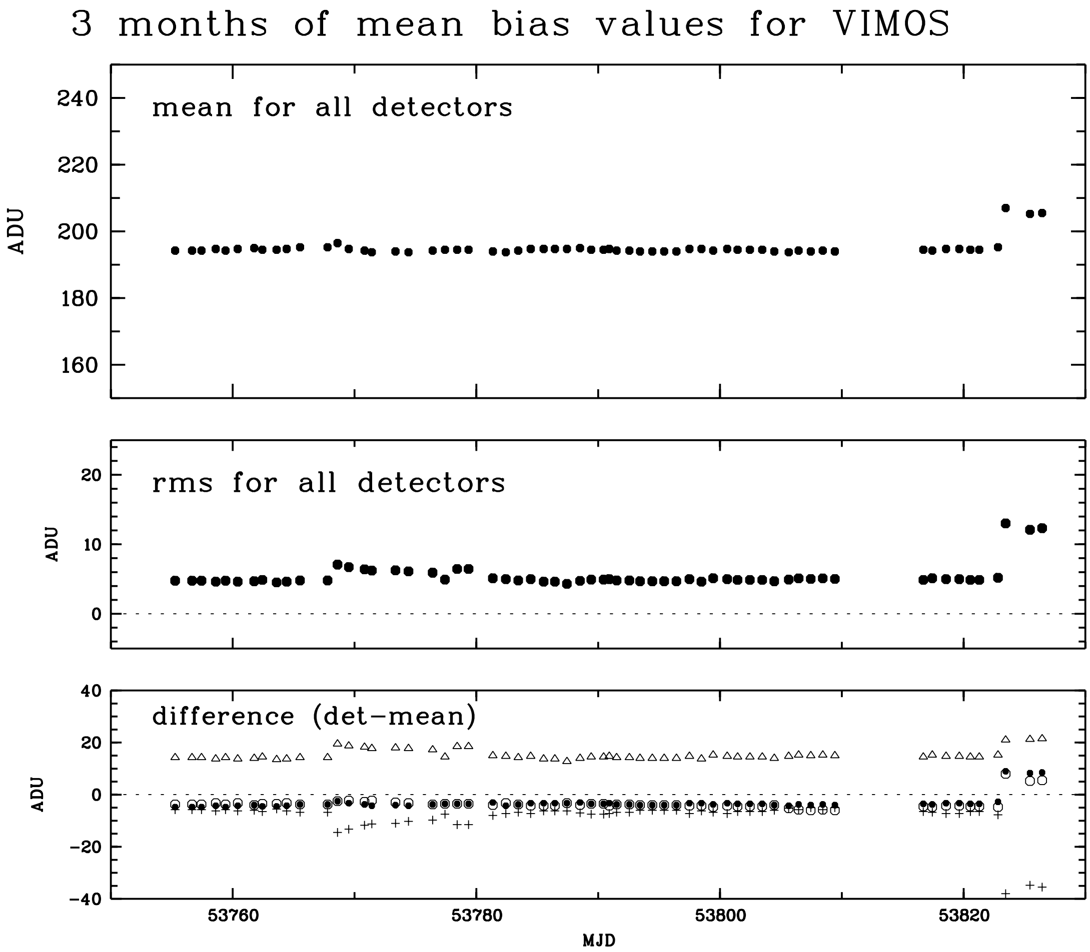

Figure 4. Trending of the mean bias level: average of all quadrants (top), corresponding rms (middle), and differences of the individual values to the average (bottom). The four quadrants are denoted by different symbols in the lower panel.

say, two sigmas from the sliding mean (dynamic threshold), or by more than a configured fixed value, the new value is flagged as outlier. The QC scientist then may decide to look closer at that product than at those which are flagged as normal.

A more advanced form of scoring is currently implemented for VIMOS. A set of key (crucial) QC parameters per product type is defined. These are checked by a scoring routine against the most recent similar values from the past two months, as stored in the QC1 database. Each parameter has a configured confidence interval. If this is violated, a flag is set. The total set of flags for the checked product is evaluated to score its compliance with the 'normal' behaviour between 0 (all flags within specifications, very unlikely to be an outlier) and 1 (all flags set, very likely to be an outlier). The score is evaluated to display green or red on a graphical display.

The scoring process can be

- scaled to arbitrary multiplicity,
- fine-tuned based on experience, thereby reflecting the growing expert knowledge of the QC scientist
- fine-tuned to focus either on gross (average) properties or on single-detector properties.

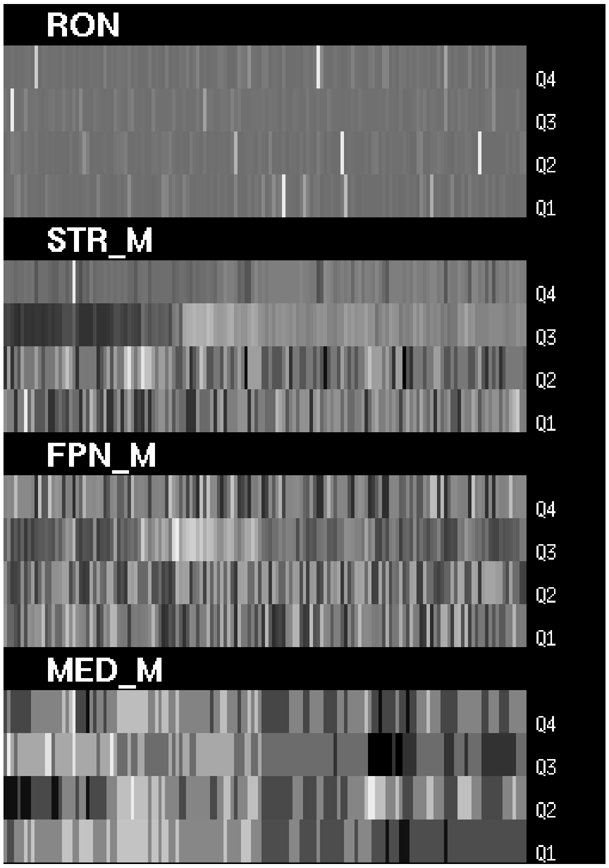

Figure 5. Example trending visualization of four VIMOS bias QC parameters: median bias level (MED_M), fixed pattern noise (FPN_M), structure (STR_M), and read-out noise (RON).

Scoring has been found to be highly efficient in detecting outliers and to assist the QC scientist in focusing on unusual behaviour ('information on demand').

3.2. Averaged QC Parameters

Another powerful concept which is still experimental is to measure and interpret *averaged* QC parameters. This concept helps to distinguish coherent changes (the ones which are shown by all detectors) from incoherent changes (one detector only).

Fig. 4 shows three months of bias values for the four VIMOS detectors. The traditional trending plot would display four parameter sets which focus on the individual behaviour of the detectors. The plot in Fig. 4 has two panels focusing on the global (coherent) trending, and a third control panel for the (differential) detector trending. The upper panel shows the average for all four detectors, while the second panel displays the corresponding rms. The lowest panel shows the four individual parameter sets, here as difference of the measured values against the mean value from the uppermost panel.

This way of visualization reveals that

- the mean value has been very stable until recently, now having jumped to a new stable value
- the rms has shown some variations between MJD ≈ 53770 and 53780, and some stronger increase correlated with the recent jump

- the difference plot shows that two of the four detectors have shown stronger instability than the other, thus causing the intermediate rms increase, and that now one detector has fallen off in comparison with the other three.

If the detectors would always change coherently, the rms value would remain stable even across the strong jump. Incoherent changes can be detected easily by increased rms even if the mean value is stable.

This technique is also expected to be scalable to higher multiplicity. Its results can also be automatically evaluated by the scoring process.

3.3. Trending Displays

Another possible solution for visualization of multi-detector QC information is to display QC values as color-coded maps. Each detector parameter set then is turned into a row, while each time point is represented as a column. As an example, we show a subset of the bias QC parameters for VIMOS in Fig.5. It shows the latest 90 measurements in all four quadrants for four selected bias parameters: median bias level, fixed pattern noise, structure, and read-out noise. Outliers for the median bias have been defined by deviating by more than 2 ADUs from the mean value of the 90 measurements. This is a rather narrow definition and consequently some outliers can be seen in the example. For the other three parameters, outliers are defined as deviating by more than 3σ from the mean.

This kind of visualization is basically appropriate to detect single outliers as can be seen for read-out noise in Fig. 5. It does, however, not provide any information about the time that has elapsed between two measurements. More important is that trends over time cannot be detected and coherent behavior of all or some of the quadrants is difficult to be seen.

4. CONCLUSIONS

We have presented solutions for managing Quality Control for multi-detector instruments and are in the process of testing these for the VLT instrument VIMOS. We make use of comparison to reference products, automated evaluation and proper visualization. The experience of these tests will be necessary in order to develop the QC process for the forthcoming survey and second generation instruments with their high multiplicity.

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