SAUNA System Beta-Gamma Detector Calibration Stability Monitoring and Correction

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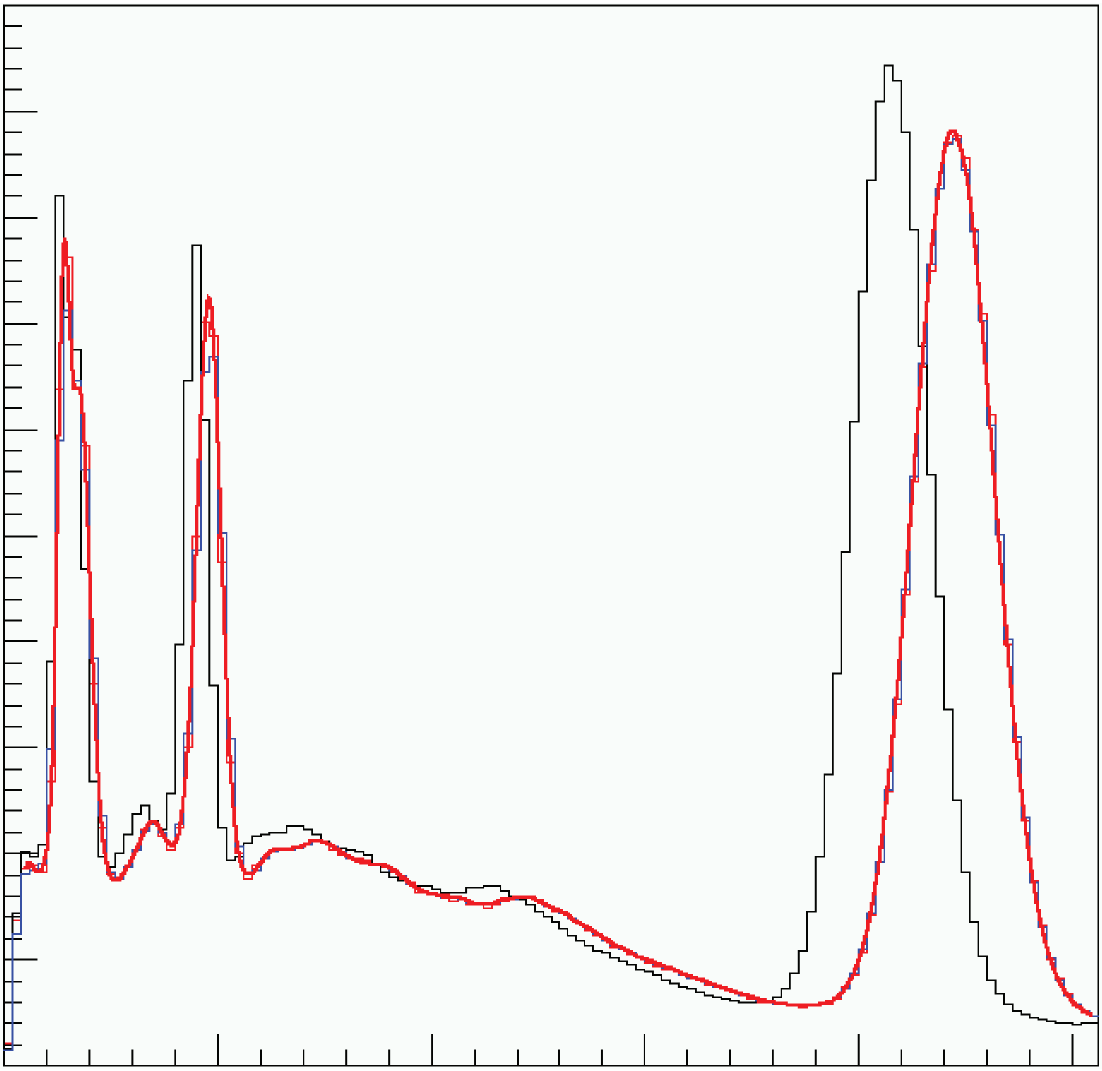

FOI-R--4469--SE
ISSN 1650-1942 November 2017

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Titel	Övervakning och korrektion av kalibreringsstabilitet i SAUNA-systemets beta-gammadetektorer
Title	SAUNA System Beta-Gamma Detector Calibration Stability Monitoring and Correction
Report no	FOI-R--4469--SE
Month	November
Year	2017
Pages	42
ISSN	ISSN-1650-1942
Customer	Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO)
Project no	E4331
Approved by	Mats Strömqvist
Division	CBRN Defence and Security

FOI Swedish Defence Research Agency

Abstract

An algorithm and implementing software has been developed to automatically monitor and correct for electronic drifting in the energy calibration of the beta- and gamma detectors of the SAUNA system. Quality control measurements done between each sample (or background) measurement are analyzed using full-spectrum fitting to a template created at the time of calibration. Any detected drifting is corrected by a change in electronics gain before the next measurement starts. Initial and long-term testing under different conditions indicate that the method allows the spectral stability to be maintained to within better than about 1 % for the electron detectors and about 0.1 % for the photon detector. Analysis of the corrective actions taken by the system indicates that the maximum deviation during the testing period (in the absence of correction) would have been about 15 %.

Keywords

Noble Gas, Xenon, SAUNA, System Performance, Detector Electronics Drifting, CTBT

Sammanfattning

En algoritm med mjukvaruimplementering har utvecklats för att automatiskt övervaka och korrigera elektronikinducerade avvikelser från energikalibreringen av SAUNA-systemets beta- och gammadetektorer. Kvalitetsövervakningsmätningar, som görs mellan varje prov- eller bakgrundsmätning, analyseras genom anpassning av hela spektrum till ett mallspektrum som skapas vid kalibreringen. Upptäckta avvikelser korrigeras genom förändring av den elektroniska förstärkningen innan nästa mätning påbörjas. Inledande prov och långtidstester visar att metoden förmår bevara spektrumstabilitet inom bättre än ungefär 1 % för elektrondetektorerna och ungefär 0.1 % för fotondetektorn. Analys av systemets korrektioner ger att den faktiska maximala avvikelsen under försöksperioden (om ingen korrektion gjorts) hade varit ungefär 15 %.

Nyckelord

Ädelgas, Xenon, SAUNA, Systemprestanda, Detektorelektronikdrift, CTBT

Contents

1 Introduction and Summary

1.1 Introduction

This report describes the development and testing of an algorithm implemented by appropriate software and hardware methods to maintain a stable energy channel number to energy calibration in SAUNA-type beta-gamma coincidence detectors.

The SAUNA system is an automatic noble-gas sampling and measurement system developed by FOI and manufactured by Scienta Sensor Systems. It is widely used world-wide, particularly in the context of the International Monitoring System (IMS) being developed for verification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The current version, used in the IMS, is SAUNA II. A new version, the SAUNA III, is in an advanced development stage. The SAUNA system, including the radiation counting system at its heart, has been described elsewhere (*e.g.* references [1], [2] and [3]); therefore only a few features especially relevant to the present work will be recapitulated and discussed here.

The SAUNA system employs beta-gamma coincidence detectors comprising a large NaI crystal for photon detection surrounding a plastic scintillator cell that holds the measured gas sample and functions as a detector for beta and conversion electrons. The signals generated by photons in the NaI crystal are read out using one photomultiplier (PM) tube, while those generated by electrons in the plastic scintillator cell are read out by two PM tubes. The pulse heights registered by the plastic scintillator cell PM tubes are summed to provide an electron energy signal.

It is well known that the response of radiation detection systems may change over time. An example from a SAUNA II system is shown in figure 1.1.

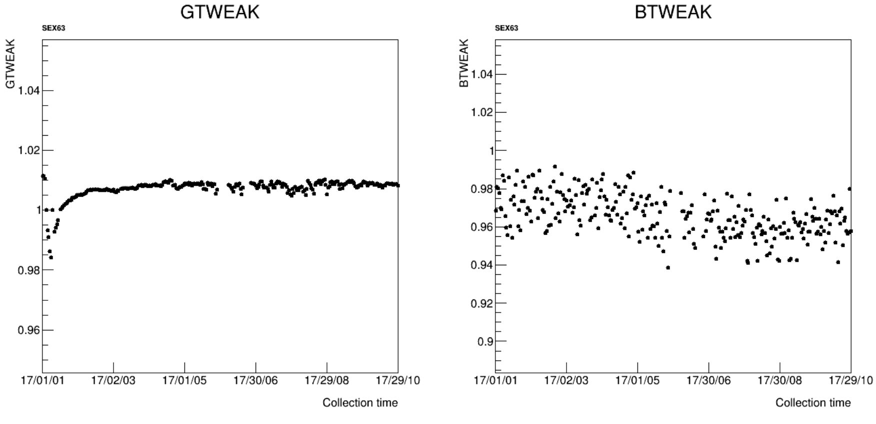


Figure 1.1: Example of detector energy calibration drift: The 'tweaking' factors that were applied in spectral analysis to compensate for changes relative to calibration in the beta-gamma detectors of the *SEX63* SAUNA II system in Stockholm during 2017. The left-hand frame shows an example of photon detector drift and the right-hand frame shows electron detector drift.

It is not feasible to perform full calibrations of the SAUNA radiation detector with very high frequency, or to have a check-source constantly present. In order to nevertheless allow high-accuracy analysis of SAUNA beta-gamma coincidence spectra, each such measurement is preceded and followed by a quality-control (QC) measurement using a radiation check source consisting of a mixture of ^{137}Cs and ^{152}Eu or sometimes ^{137}Cs only. The QC spectra associated with each sample or gas background measurement are typically used to check for detector calibration shifts and if necessary modify analytical Regions of Interest (ROIs) accordingly. The methods implemented in *e.g.* FOI's *xecon* software [4] work well and allow analytical results to be treated with high confidence. Nevertheless, the process represents a complication and a potential source of error that would not be necessary if spectral stability could be maintained over time at the source, *i.e.* automatically by the counting system itself.

The method presented in this report, with implementing software and hardware aspects, allows the SAUNA system to deliver photon and electron spectra that remain stable in energy calibration over time. The main results are summarized in the next section.

1.2 Summary

Using automatic analysis of QC spectra preceding each sample and gas background measurement, the electronic gain for each detector channel can be corrected before each such measurement to maintain spectral stability over time.

The method has been implemented through an extension to existing SAUNA II operational software in the form of a new Windows Service called SAUNA_DRIFT and modifications to the existing SAUNA_PHDAQ Windows Service. The former determines the spectral drift and computes appropriate electronics gain changes to compensate for it, and the latter executes the gain changes. The analysis algorithm is described in chapter 2, and its implementation in chapter 3. The algorithm and its implementation have been tested both with regard to intrinsic performance (section 4.1) and with regard to stability and operability (section 4.2). Finally, a long-term (about three months) test has been carried out with the new software running as part of the SAUNA II control software performing atmospheric measurements and utilizing new and more precise QC source emplacement mechanisms (section 4.3).

No operational or software stability issues have been noted during the course of the long-term testing. Spectral stability, defined as consistency with a high-statistics 'master QC' spectrum, is achieved with a precision of 0.5 % for beta pulse height spectra, and a factor 10 better for NaI photon energy spectra.

Input and output from the spectral stability monitoring is via the SAUNA on-board database. Relevant parts of the information stored can be provided to end-users in the form of extensions to the pulse-height data and state of health files automatically sent by the system. Suggested extensions to the formats are given in chapter 5.

2 Algorithm

2.1 SAUNA Data Acquisition

The signals from the three channels (one NaI scintillator PM tube and two plastic scintillator PM tubes) of each SAUNA detector are read out by a DGF Pixie-4 digital waveform acquisition and spectrometer card. The card and its functionality are described in detail in the manufacturer's documentation (see references [5], [6] and [7]). In short, it digitizes and histograms the pulses that form events of interest. Histograms are stored in an external memory awaiting download by the host computer (*i.e.* the SAUNA control PC). The SAUNA version of Pixie-4 stores five one-dimensional spectra and two two-dimensional spectra in histogram form as detailed in table 2.1.

Signal(s)	Parameter	Size (bins)	
		stored	output
NaI singles	Photon energy	8192	256
Plastic singles 1	PM tube 1 pulse height	8192	
Plastic singles 2	PM tube 2 pulse height	8192	
Plastic sum 1 + 2	Electron energy	8192	256
Plastic diff./sum ratio	Electron hit "position"	256	
Plastic 1 vs plastic 2	Plastic pulse coinc.	128 x 128	
NaI vs plastic sum	Electron-photon coinc.	256 x 256	256 x 256

Table 2.1: The spectral information produced by the SAUNA data acquisition system and (in the right-most column) the spectral products packaged as IMS files and delivered as final output by the system. The "Plastic diff./sum ratio" histogram is produced by dividing the difference of the two plastic scintillator pulse heights by their sum, adding one and multiplying the result by 128, to yield a number in the range 0 – 256 that indicates how the total signal was divided between the two PM tubes connected to the plastic scintillator cell — a rough indicator of the interaction position along the cylindrical cell.

The table also shows the spectra that are provided in the SAUNA II final products (in the form of IMS 2.0 files), and their final binning (size). The reduction in size is achieved by retaining only the lower half of the bins in ADC dynamic range (*i.e.* 4096 bins) and re-binning these by a factor of 16. However, the SAUNA software itself, including the present new development, has access to the full range of histogrammed information at the full dynamic range and resolution. In particular, this allows the present algorithm, which is intended to be used as part of the system software, to make use of plastic scintillator singles pulse height spectra rather than the sum of the signals (*i.e.* the electron energy spectrum). It would also allow the use of higher-resolution spectra than those delivered as system output, but this turned out not to be necessary (see section 2.5).

SAUNA depends on the Windows service SAUNA_PHDAQ to communicate with the Pixie-4 electronics in order to read or set parameters of operation, start or stop data acquisition and download histogrammed data. SAUNA_PHDAQ in turn carries out these tasks according to instructions/parameters (*e.g.* desired measurement state, Pixie boot settings or spectral re-binning factors) that it reads from the SAUNA system database. In coding terms, it uses the C library functions of the Pixie-4 Application Program Interface (API) to communicate with the Pixie electronics. The API allows the calling software to interact with Pixie *inter alia* by specifying values of C global variables, out of which the variable *VGain* is of particular interest at present. The user-specified value of *VGain* for a given signal channel is used by Pixie to set both an analog gain for input signal conditioning prior to digitization and a digital 'fine-tuning' factor that is applied to the digitized values in order to compensate for any remaining difference between the analog voltage gain and the user-desired value.

2.2 Gain Stabilization Concept

Previous electronics gain correction methods developed and employed by FOI have been intended for use in the spectrum analysis stage. Given an IMS-format beta-gamma spectrum file, the locations of spectral peaks with known energy have been compared to the locations expected given the original calibration information in the file header. For the peak-less electron spectra, the energy conservation properties of Compton scattering beta-gamma coincidences produced by the QC source were used to compute the energy of 'peaks' in electron cuts along a Compton distribution at known photon energy (see *e.g.* reference [2]). Linear, and in some cases constant offset, changes in the energy-to-bin relationship have been determined and applied to the ROI limits that correspond to the original calibration. The result has been ROI contents insensitive at least to small and linear changes in spectrum calibration.

In order to provide an algorithm more suitable for automatically stabilizing spectral gain without reference to any energy-to-channel calibration, a method was developed to compare each short and regularly occurring QC measurement with a reference 'master QC' *template* spectrum and determine the linear gain shift. These measurements are 30 minutes and a few hours long, respectively. The comparison does not employ specific peaks at known locations, but performs a least-squares fit of the entire 'monitored' spectrum (or large parts of it) to the template. In the current implementation, the only free parameter in the fit is a linear transformation coefficient, called the *gain* G.

Thus, the assumption is that if the pulse heights that were histogrammed to yield the template spectrum had all been transformed by the constant *gain* factor G before histogramming, the calibration of the template spectrum would be the same as that of the monitored spectrum. The factor G is assumed to be the gain shift factor sought, and is used by modifying the *VGain* setting (see section 2.1) for the next measurement following by $1/G$. The fitting also employs a global scaling factor since the counting time for the monitored spectra is assumed to be quite different from that of the template spectrum. The scaling factor, however, is fixed to the ratio of the live counting times of the two spectra. G is the only free parameter.

Note that there are important differences between applying corrections to ROI limits, or to spectra themselves offline and applying instead corrections to the electronics that produce the spectra. In particular, the SAUNA electron energy spectrum is produced by summing signals from two independent PM tubes with separate electronics channels. These channels may well exhibit different drifting behavior. In other words a gain shift analysis based on the energy spectrum can not be applied to correct the electronics. For this application, the individual outputs from the two PM tubes must be analyzed individually and corrections applied individually. However, features in the individual pulse-height spectra have no particular Compton energy relationship with the photon spectrum. Producing instead a three-dimensional photon − electron pulse height 1 − electron pulse height 2 histogram did not seem an attractive solution. This was the main reason for investigating the use of full-spectrum fitting rather than making use of the previously existing peak-based procedure.

The log-likelihood fit is performed using the Minuit package as implemented for the ROOT [8] physics analysis package (see section 3.2. Best results are obtained when bin integrals rather than bin center values are fitted. However, in this case the discontinuities introduced by discrete spectrum bin limits can introduce numerical difficulties in the fit. Therefore, the function that is actually fitted to the gain monitoring spectrum is not the actual template histogram, but is derived from it by constructing a cubic spline function from the template spectrum bin contents.

To summarize, a function $f_G(x)$ is fitted to the monitoring histogram h_{x_i} in order to obtain the optimum value of the gain G. The function $f_G(x)$ is obtained from the template histogram t_{x_i} by construction of a cubic spline $t_3(x_i)$ from the bin contents of t_{x_i}. Specifically, the function $f_G(x)$ is of the form:

$$f_G(x) = k \cdot \frac{1}{G} \cdot t_3(\frac{x}{G}) \tag{2.1}$$

where k is the fixed global scaling factor that accounts for different spectrum live acquisition times.

An example of the fitting procedure is illustrated in figure 2.1. The template spectrum in the case illustrated was collected during five hours, and the gain monitoring spectrum during 30 minutes. The fitted range (bins 5-255 for the NaI and 10-230 for the plastic scintillator spectrum) is indicated by plot range of the fitted function (thin green curve).

2.3 Demonstration

A SAUNA beta-gamma detector was used to collect 101 30-minute measurements with a ^{137}Cs source in the QC position. For each measurement after the first, *VGain* was increased by 0.1 % of the initial value, so that in the final measurement the *VGain* values were 10 % higher than in the first measurement. A five-hour measurement with the same source and geometry was used as template.

Figure 2.2 shows the gains determined by the algorithm (relative to the template) using the histogram rebinning factors (see section 2.5) 2 for NaI photon energy spectra and 4 for beta pulse height spectra.

Figure 2.3 shows the distributions of deviations of fitted gains from the known relative *VGain* setting (0 – 10 %). The standard deviations of these distributions constitute a measure of the precision of the gain monitoring algorithm, and were used to optimize the fitting options and various parameters of the algorithm (see section 2.4). Typically, as in the figure, the standard deviations are about 0.05 % for the NaI energy spectra and about 0.4 % for the beta pulse height spectra. Slight biases of about 0.04 % for NaI energy and 0.3 % for the beta 2 pulse heights are evident in the figure. A check using the first 30-minute measurement as template instead of the 5-hour measurement suggests, although with considerably less precision, that the cause of this effect is not a bias in the algorithm but an actual shift in the spectral gain between the 5-hour reference measurement and the series of 30-minute measurements. Note that in the intended normal operating mode, where corrective changes would be applied to *VGain* in response to any spectral shift detected in each measurement, this shift would not appear.

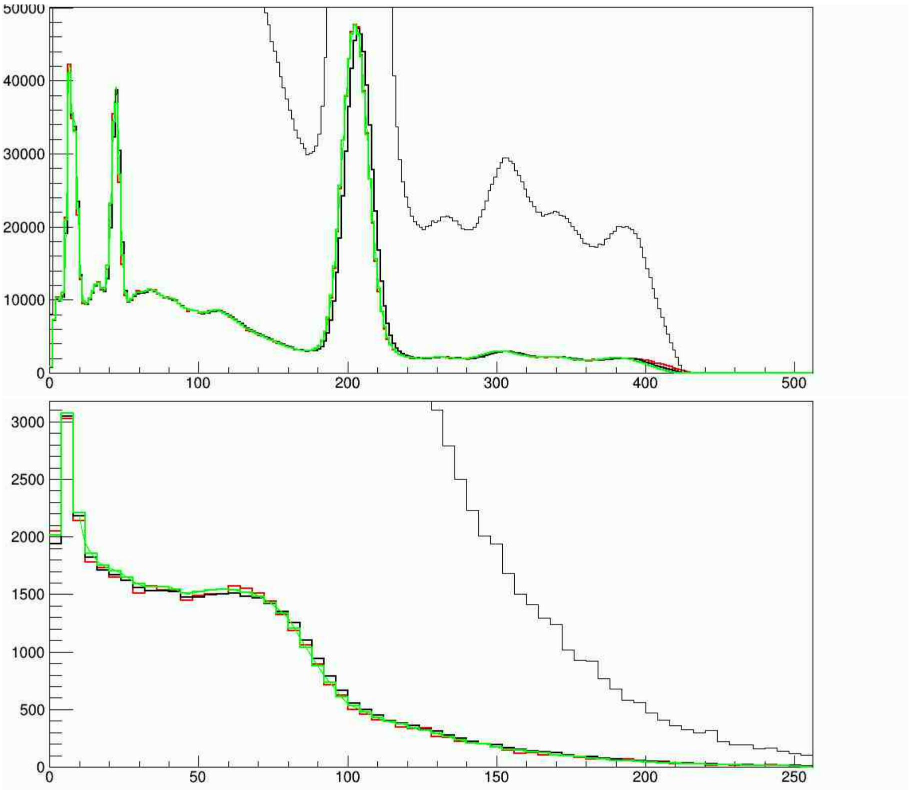


Figure 2.1: Scaled template spectrum (black) compared to gain monitoring (red) spectrum, both from a mixed ^{137}Cs and ^{152}Eu source. Photon (NaI) energy spectra are shown in the top frame and electron (plastic scintillator) pulse height spectra in the lower frame. Thin black line: original template spectrum (unscaled by the live times ratio). Thin green curve: fit function (the cubic spline function described in the text). Green histogram: result of transforming the template using the fit parameter G. According to the fit, the NaI spectrum has shifted 1.189 ± 0.007 % from the template, and the plastic scintillator spectrum has shifted 2.4 ± 0.3 %.

2.4 Fitting Options

The ROOT software library (see section 3.2) used in the implementation of the algorithm offers a number of options when fitting a function to a histogram. These include

- χ^2 or log-likelihood fitting.
- Fitting function values at the center of histogram bins or the integrals of the function over the bins.

Options were selected based on the standard deviation of the fitted gain from known *VGain* settings in the series of 101 30-minute measurements (with a 5-hour measurement as template) described in section 2.3. Table 2.2 shows a comparison (using the same rebinning factors – see section 2.5 – of 2 and 4 for NaI and beta, respectively, as in section 2.3), based on which it was decided to use log-likelihood fitting and bin integration.

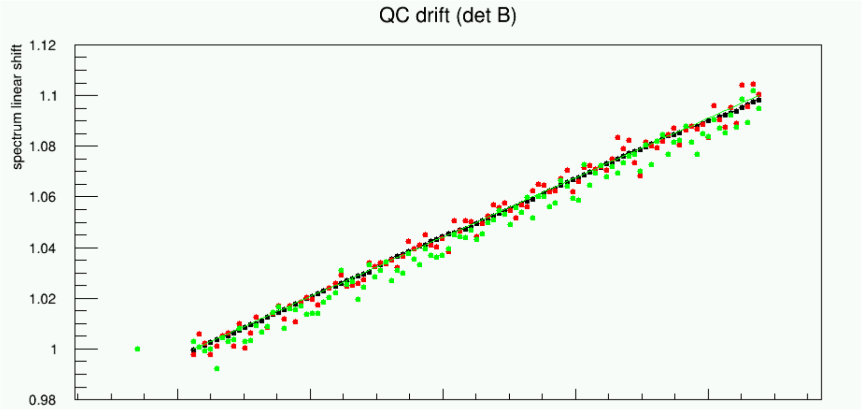


Figure 2.2: Gain monitoring algorithm response to an applied constant drift in a series of 101 30-minute measurements of a ^{137}Cs source. Black: NaI energy spectrum; Red: beta 1 pulse heights; Green: beta 2 pulse heights.

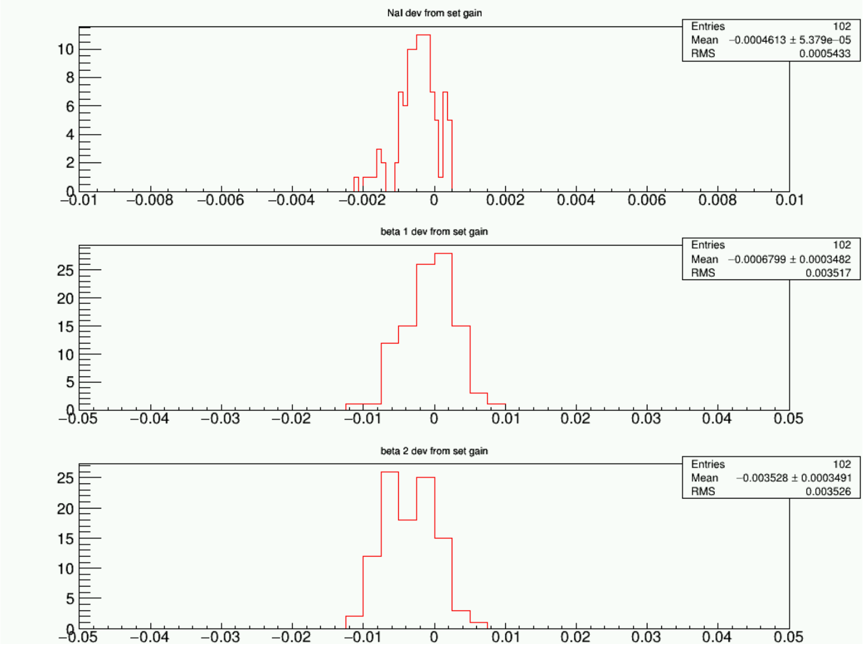


Figure 2.3: Distributions of deviations of fitted gains from the known relative (to template) *VGain* settings.

2.5 Range and Binning of Spectra

For the NaI photon energy spectra, only the lower half of the range histogrammed by the Pixie electronics is used in the data reported by the system. In energy this corresponds to from 0 to just above 662 keV. The original histogram, stored on the system, has 8192 bins. SAUNA II rebins the lower 4096 bins a factor of 16 into 256 bins. The spectral drifting analysis software (SAUNA_DRIFT – see section 3.1) has the capability to further compress the spectra it uses for gain monitoring; the additional factor by which the standard 256-bin histogram should be compressed is hard-coded as a preprocessor #define statement. A factor 2 (for a total of 128 bins) was used to obtain the

Type of fit	function evaluation	spectrum NaI	 beta 1	 beta 2
Likelihood	integration	0.054	0.35	0.35
Likelihood	bin centre	0.054	0.36	0.36
χ^2	integration	0.054	0.37	0.36
χ^2	bin centre	0.054	0.38	0.37

Table 2.2: Standard deviation of fitted gain from set *VGain* for different fitting options.

NaI results presented above. Both a factor 1 and a factor 4 yield slightly worse precision than a factor 2, and for higher binning factors (8 and 16) the lowest-energy photon peak starts to merge with the low-energy threshold. Although a factor 8 in the case examined actually yielded slightly better precision than factors 1, 2 and 4 it was decided to use factor 2 and not to risk corrupting spectral features too much.

After the initial tests (reported in sections 4.1 and 4.2), it was noted that the standard gain settings of the NaI detectors are such that in some cases (though not in the actual test measurements) the 662 keV peak of ^{137}Cs will have very little background visible beyond its high-energy edge. The peak itself may even be somewhat truncated by the upper edge of the spectrum. Therefore, it was decided to use the full available NaI energy range for the purpose of gain stabilization analysis. This change was implemented before the start of the long-term test (reported in section 4.3).

The plastic (electron detector) pulse height spectra also have 8192 bins as originally histogrammed, and SAUNA II compresses the lower half of the dynamic range by a factor of 16 into 256 bins. The beta pulse height spectra have fewer sharp features than the NaI photon energy spectra, and it might be expected that further compression in order to improve bin statistics would be beneficial. In fact, based on the 102 test measurements described above, an additional compression by a factor 4 (into 64 bins) results in better precision than factor 1 or factor 2. Further compression does not improve the precision significantly, and eventually the precision gets worse. It was decided to use a factor 4 compression for the beta pulse height histograms used by SAUNA_DRIFT.

3 Software

3.1 Functionality

The SAUNA system software depends on several Windows services that perform various functions such as issuing commands to and receiving data from the detector electronics. The spectrum comparison algorithm described in chapter 2 has been implemented as a new Windows service: SAUNA_DRIFT.

SAUNA_DRIFT checks the SAUNA system database at preset (short) intervals for the appearance of newly completed quality control (QC) measurements. If a new QC spectrum measurement is found, the service applies the new spectrum comparison algorithm to determine any gain shift relative to a designated *template* measurement. If so configured (through the appropriate flags in the *Configuration* table of the system database), a change in the *VGain* setting for each detector is requested by writing a new value to the **_NEXT_VGAIN* parameter in the *Configuration* table. The SAUNA_PHDAQ service controlling measurements has been modified to upload the value of this parameter to the Pixie detector electronics each time it starts a new measurement. Thus, the *VGain* detector setting determined by SAUNA_DRIFT is updated next time the SAUNA_PHDAQ service starts a measurement using that detector.

Each time the SAUNA_DRIFT service performs a gain shift analysis, it records some results in the monitored QC measurement's row of the *Acquisition* table of the system database (see details in section 3.4).

3.2 Structure

The software uses fitting and histogram handling tools from the Root physics analysis package developed at CERN [8]. All Root-dependent functionality is confined to a separately compiled dynamically linked library *wcorr_cpp.dll.* This library was produced with Root version 5.34/34 (Visual Studio Windows binary distribution). The source code is in the file *wcorr.cpp* and the headers needed are in the file *wcorr.h.* The Windows service SAUNA_DRIFT calls the Root-dependent routines through the pure C function *call_wcorr()*, also defined in *wcorr.cpp.*

The source code for SAUNA_DRIFT is in the files *SAUNA_DRIFT_main.cpp* and *SAUNA_DRIFT_base.cpp.* The latter defines little more than the service name. Headers are in *SAUNA_DRIFT_main.h* and *SAUNA_DRIFT_base.h.*

Some changes were made to the SAUNA_PHDAQ Windows service that controls the detector electronics, and to the SAUNA system database. The changes were made in order to accommodate settings for gain monitoring (in the *Configuration* table), the recording of gain monitoring information (mostly in the *Acquisition* table) and requests for *VGain* changes to be made by SAUNA_PHDAQ (through the *Configuration* table). A new 'software user' *SAUNA_DRIFT* was also created.

3.3 Settings

The behavior of the gain monitoring and correction service SAUNA_DRIFT is controlled by entries in the *Configuration* table of the system database. Table 3.1 shows these entries in the *Configuration* table.

The *DETECTOR*_BOOT_VGAIN_** parameters are recorded at boot time by the SAUNA_PHDAQ service. They are the values of *VGain* for each module stored in the Pixie setup file and uploaded by SAUNA_PHDAQ to the Pixie crate when this service starts.

The *DETECTOR*_NEXT_VGAIN_** parameters on the other hand are read by the SAUNA_PHDAQ service and uploaded to the Pixie crate as part of the sequence preceding any measurement started by SAUNA_PHDAQ. By changing the value of one of them, it is possible to request a change in *VGain* for the corresponding detector. This is the mechanism by which SAUNA_DRIFT effects a gain change as a result of its drift analysis.

The *GAINCORR_REFERENCE_** parameters are checked by the SAUNA_DRIFT service each time it finds a new QC measurement in the system database and launches a gain shift analysis. By entering a new acquisition ID it is possible at any time to change the measurement used as template for the gain shift analysis.

The **_FITWIN_LOW_** and **_FITWIN_HIGH_** parameters determine what part of the monitored and template spectra are used in the gain shift analysis. Those portions that lie between the limits are used, the lower and higher portions of the spectra are disregarded. These parameters are checked by the SAUNA_DRIFT service each time it finds a new QC measurement in the system database and launches a gain shift analysis.

If the *DRIFTCORR_*_** parameters are set non-zero following a successful gain shift analysis, the SAUNA_DRIFT service requests a *VGain* change for the corresponding detector by multiplying the *Acquisition* table value of **_Pixie4_VGain* (see table 3.2) for that measurement (*i.e.* the value of *VGain* that was used) by $1/G$ and writing the result to *DETECTOR*_NEXT_VGAIN_**. If the gain shift analysis failed (bit 7 in the **CorrFlag* flag was set – see table 3.3), no new value of *DETECTOR*_NEXT_VGAIN_** is written to the database even if the *DRIFTCORR_*_** parameter is non-zero.

3.4 Output

The gain monitoring and correction service SAUNA_DRIFT records gain shift analyses by populating several new fields in the monitored QC measurement's row of the *Acquisition* table of the system database. Table 3.2 shows these new columns in the *Acquisition* table.

The **_Pixie4_VGain* values are not strictly SAUNA_DRIFT output, but are used together with the output from this service. They are the set values of *VGain* used during a detector measurement, and are recorded at acquisition start by the SAUNA system database server through the *startnewacquisition_internal* function, which is executed in the course of starting any new measurement.

The **CorrFlag* words are 8-bit flags that record information about the performance of the gain monitoring algorithm. The meaning of each bit of the correction flags is explained in table 3.3.

The setting of bits 0 (indicating "error in MIGRAD"), 2 (very high χ^2 per degree of freedom), 4 (Root flagged "Fit not valid") and/or 6 (live time ratio inconsistent with counts ratio by > 90 %) indicate potentially serious enough problems that no gain correction is performed on the basis of the analysis. If any of these bits are set, bit 7 (indicating 'gain correction not performed') is also set and SAUNA_DRIFT does not request any gain changes.

Row	Id	Key	Value (*examples*)	Info
132	134	DETECTORA_BOOT_VGAIN_G	1	The Pixie VGAIN for Det A NaI channel as given by Pixie set file at boot
133	135	DETECTORA_BOOT_VGAIN_B1	2	The Pixie VGAIN for Det A beta 1 channel as given by Pixie set file at boot
134	136	DETECTORA_BOOT_VGAIN_B2	2	The Pixie VGAIN for Det A beta 2 channel as given by Pixie set file at boot
135	137	DETECTORB_BOOT_VGAIN_G	5.99997	The Pixie VGAIN for Det B NaI channel as given by Pixie set file at boot
136	138	DETECTORB_BOOT_VGAIN_B1	4	The Pixie VGAIN for Det B beta 1 channel as given by Pixie set file at boot
137	139	DETECTORB_BOOT_VGAIN_B2	4	The Pixie VGAIN for Det B beta 2 channel as given by Pixie set file at boot
138	140	DETECTORA_NEXT_VGAIN_G	1	The Pixie VGAIN for Det A NaI channel that will be set for next acquisition
139	141	DETECTORA_NEXT_VGAIN_B1	2	The Pixie VGAIN for Det A beta 1 channel that will be set for next acquisition
140	142	DETECTORA_NEXT_VGAIN_B2	2	The Pixie VGAIN for Det A beta 2 channel that will be set for next acquisition
141	143	DETECTORB_NEXT_VGAIN_G	6.50997	The Pixie VGAIN for Det B NaI channel that will be set for next acquisition
142	144	DETECTORB_NEXT_VGAIN_B1	4.34	The Pixie VGAIN for Det B beta 1 channel that will be set for next acquisition
143	145	DETECTORB_NEXT_VGAIN_B2	4.34	The Pixie VGAIN for Det B beta 2 channel that will be set for next acquisition
144	146	GAINCORR_REFERENCE_A	17112	The acq. ID of the measurement to be used as a template for Det A gain monitoring
145	147	GAINCORR_REFERENCE_B	17646	The acq. ID of the measurement to be used as a template for Det B gain monitoring
146	148	BETA1_FITWIN_LOW_A	10	Det A lower-limit fitting window for beta 1 QC pulse height
147	149	BETA2_FITWIN_LOW_A	10	Det A lower-limit fitting window for beta 2 QC pulse height
148	150	BETA1_FITWIN_HIGH_A	230	Det A upper-limit fitting window for beta 1 QC pulse height
149	151	BETA2_FITWIN_HIGH_A	230	Det A upper-limit fitting window for beta 2 QC pulse height
150	152	BETA1_FITWIN_LOW_B	10	Det B lower-limit fitting window for beta 1 QC pulse height
151	153	BETA2_FITWIN_LOW_B	10	Det B lower-limit fitting window for beta 2 QC pulse height
152	154	BETA1_FITWIN_HIGH_B	230	Det B upper-limit fitting window for beta 1 QC pulse height
153	155	BETA2_FITWIN_HIGH_B	230	Det B upper-limit fitting window for beta 2 QC pulse height
154	156	DRIFTCORR_NAI_A	1	Set ‘0’ for no drift correction on Det A NaI
155	157	DRIFTCORR_B1_A	1	Set ‘0’ for no drift correction on Det A beta 1
156	158	DRIFTCORR_B2_A	1	Set ‘0’ for no drift correction on Det A beta 2
157	159	DRIFTCORR_NAI_B	1	Set ‘0’ for no drift correction on Det B NaI
158	160	DRIFTCORR_B1_B	1	Set ‘0’ for no drift correction on Det B beta 1
159	161	DRIFTCORR_B2_B	1	Set ‘0’ for no drift correction on Det B beta 2
160	162	NAI_FITWIN_LOW_A	5	Det A lower-limit fitting window for gamma spectrum
161	163	NAI_FITWIN_HIGH_A	255	Det A upper-limit fitting window for gamma spectrum
162	164	NAI_FITWIN_LOW_B	5	Det B lower-limit fitting window for gamma spectrum
163	165	NAI_FITWIN_HIGH_B	255	Det B upper-limit fitting window for gamma spectrum
164	166	QC_CHECK_SET_INTERVAL_s	5	Number of seconds between checks for new QC measurements

Table 3.1: SAUNA_DRIFT-related new entries in the *Configuration* table.

Column	Content
NaI_Pixie4_VGain	Value of NaI *VGain* during the measurement
Beta1_Pixie4_VGain	Value of beta 1 *VGain* during the measurement
Beta2_Pixie4_VGain	Value of beta 2 *VGain* during the measurement
GainCorrReference	Acq. ID of the template used to check for drifts
NaICorrFlag	Flag with information about algorithm performance for NaI energy
NaIDrift	Gain change (drift) of NaI energy spectrum relative to template
B1CorrFlag	Flag with information about algorithm performance for beta 1 pulse height
B1Drift	Gain change (drift) of beta 1 pulse height spectrum relative to template
B2CorrFlag	Flag with information about algorithm performance for beta 2 pulse height
B2Drift	Gain change (drift) of beta 2 pulse height spectrum relative to template

Table 3.2: Content of SAUNA_DRIFT-related columns in the *Acquisition* table.

Bit	Value	Meaning if set
0	1	Error in MIGRAD
1	2	Error in HESSE and/or MINOS
2	4	χ^2 per degree of freedom > 1000
3	8	Error in IMPROVE
4	16	Root fitter signaled “Fit not valid”
5	32	Live time ratio inconsistent with counts ratio by > 10 %
6	64	Live time ratio inconsistent with counts ratio by > 90 %
7	128	Gain correction not performed

Table 3.3: Interpretation of the various bits of the **CorrFlag* words in the *Acquisition* table.

4 Testing and Results

Following the development of the algorithm and software, several long test series were performed in order to

- test and quantify the performance of the analysis algorithm and the implementing software under various circumstances,
- test and quantify the feasibility of spectral drift compensation by modification of the *VGain* parameter and
- ensure the stability of the software over time, including in regard to the integration with the rest of the SAUNA operating software.

One test series was carried out at FOI using a standard SAUNA II beta-gamma detector placed in an improvised (lead brick) background shield and using older SAUNA software with many local modifications. The objective was to obtain a large number of measurements of comparable quality to SAUNA II IMS QC measurements, primarily for evaluation of the algorithm itself and the chosen method of drift compensation. This test series comprised 4835 consecutive 30-minute measurements over a period of 80 days (2016-07-08 through 2016-09-26) and is described in section 4.1 below.

Another test series was carried out at Scienta Sensor Systems (the manufacturer of SAUNA II) using the standard detectors of the *IMS27* SAUNA II system [9]. The objective was to test the stability and operability of the software when operating in close to normal IMS mode (*i.e.* one 30-minute QC measurement every 12 hours, interspersed between the sample and gas background measurements). An 'advanced prototype' version of the drift control software was used, embedded in the latest SAUNA II operating software. This test series comprised about 80 measurements for each of the two detectors over a period of 42 days and is described in section 4.2.

Finally, a 'long-term' test was carried out over a period of more than four months to ensure that the performance and stability demonstrated in the initial tests could be maintained over an extended period of time while performing normal atmospheric measurements with a QC source moving in and out of position between sample and gas background measurements. This test is described in section 4.3.

4.1 Drift Control Check Using Intensive QC Measurements

The algorithm and implementing software was tested by a large number of back-to-back 30-minute measurements using a SAUNA beta-gamma detector with a standard (^{137}Cs/^{152}Eu) QC source placed permanently in the measurement position. The gain monitoring and correction software operated by analyzing spectral position (*i.e.* 'gain') in each new QC measurement. The test was carried out in three phases: an initial one with gain stabilization based on the drift analysis engaged (section 4.1.1), a second one with gain stabilization disengaged (section 4.1.2) and finally a phase with the gain stabilization re-engaged in order to test recovery and maintenance of stable operation. Phase 2 included at the end a 'provocation' or stress test using direct heating of the detector assembly using a table lamp. This was done in order both to study the dependence of detector spectral drift on temperature and to present an

	Start date	End date	Days	Measurements	Comments
phase 1	2016-07-08	2016-08-10	34	1549	Monitoring and stabilization
phase 2	2016-08-10	2016-09-02	23	1088	Monitoring only
phase 3	2016-09-02	2016-09-26	24	1113	Regain stability

Table 4.1: Summary of the test series carried out at FOI (described in section 4.1).

additional challenge to recovery of spectral stability (in phase 3 that followed immediately after). The parameters are summarized in table 4.1.

The template spectra used were collected during a 5-hour measurement (*i.e.* ten times longer than a normal QC measurement). Four days elapsed between the template measurement and the start of the test measurements.

4.1.1 Stabilization by *VGain* Compensation Engaged

In an initial phase, spectral shift analysis results were used to generate new *VGain* values for the next measurement, in order to maintain spectral stability relative to the template measurement.

Figure 4.1 shows the resulting spectral positions determined by the software (points) as well as the *VGain* values requested by the software as a result of the drift analysis (lines). The readings (one every five minutes) of a temperature sensor in the room are also shown (blue), normalized to the average temperature during the template measurement. The lower, enlarged portion of the figure (b) shows clearly the close correlation of the ambient temperature with the magnitude of gain corrections required to keep the spectra stable. The considerable difference in precision between the plastic scintillator pulse height spectra (red and green) and the NaI photon energy spectrum (black) is also evident.

The fact that the *VGain* settings required to keep the spectra unshifted relative to the template are different from the settings used for the template (*i.e.* the solid black, red and green lines are systematically shifted from one) is likely to be due to shifts occurring between the time of the template measurement and the test measurement series, not to a bias in the algorithm or implementing software. Such an effect was observed in the development data (see section 2.3) and can also be seen from the data series taken with constant *VGain* values (see section 4.1.2 below); when a standard 30-minute QC measurement in this series is used as a template instead of the 5-hour one taken before the beginning of the test, no bias is seen.

Using the temperature data, two periods during phase 1 were selected: one with comparatively stable temperature and one with comparatively high temperature variability. Spectral positions for the measurement series could then be studied for the data series as a whole, and also for the two sub-phases, yielding some idea of tha influence of ambient temperature on the detector behavior.

Figure 4.2 shows histograms of the spectral positions (relative to the template spectra), allowing the determination of the precision and accuracy of the drift control. Data are presented for the entire phase 1 and for the sub-periods with low- and high temperature variability separately. The precision (RMS width of the distributions) is about 0.5 % for the plastic scintillator electron detectors and 0.05 % for the NaI photon detector. The accuracy (distance from zero relative displacement) is within about 10^{-4} for the electron detectors and 10^{-5} for the photon detector. The difference in performance for the two types of spectra might be expected due to the availability of well-defined features such as full-energy peaks in the NaI spectrum.

It is well known that the light yield of NaI(Tl) detectors decreases with increasing temperature (see Knoll [10], figures 8–9). The measurements performed during this work confirm this behavior. A high degree of correlation between ambient temperature and detector drifting (or equivalently: compensation needed to prevent drift) is obvious from the results. The temperature conditions during the test series are summarized in table 4.2.

	Start date	End date	Measurements	Mean temp	Temp variation
template	2016-07-04	2016-07-04	1 (5 h)	19.4	0.08 %
full phase 1	2016-07-08	2016-08-10	1549	20.0	2.39 %
low temperature variability phase 1	2016-07-13	2016-07-19	304	19.3	0.22 %
high temperature variability phase 1	2016-07-31	2016-08-07	305	20.6	2.28 %

Table 4.2: Ambient temperature variability during phase 1 of the test series carried out at FOI (described in section 4.1.1), including the (longer) template measurement and the segments of the series selected as having comparatively stable temperature and comparatively highly variable temperature, respectively. A 1 % variability at a mean temperature of 20 degrees C (293.15 K) corresponds to minimum and maximum temperature in the interval being separated by 2.9 degrees.

4.1.2 Stabilization by *VGain* Compensation Disengaged

Following the initial phase, the gain compensation was switched off, though the analysis (drift determination) remained active. *VGain* settings remained unchanged at the values they had at the end of the initial phase. Figure 4.3 shows the resulting spectral positions determined by the software as well as the (now fixed) *VGain* values.

Figure 4.4 shows histograms of the spectral positions (relative to the template spectra). As for phase 1, data are presented for the entire phase 1 and for the sub-periods with low- and high temperature variability separately. The temperature conditions during the test series are summarized in table 4.3. The precision (RMS width of the distributions) for the beta channels is similar to the case for phase 1, except for the high-temperature variability period, where it is slightly worse. This may be because the intermittent temperature surges evident from figure 4.3 only affect a relatively small number of measurements to a degree comparable with the analytical precision in determining the spectral position, and do not affect the RMS measure of distribution width appreciably. For the NaI detector, where the analytical precision in determining spectral position is much better, a large difference can be seen compared to the phase 1 results.

Near the end of phase 2, a lamp was used to directly heat the detector assembly, resulting in the large disturbance seen at the rightmost edge of figure 4.3, again demonstrating the effect of temperature on the spectral stability

	Start date	End date	Measure-ments	Mean temp	Temp variation
template	2016-07-04	2016-07-04	1 (5 h)	19.4	0.08 %
full phase 2	2016-08-10	2016-09-02	1082	20.1	1.56 %
phase 2 (pre-lamp)	2016-08-10	2016-08-29	905	19.9	4.01 %
low temperature variability phase 2	2016-08-10	2016-08-17	328	19.4	0.30 %
high temperature variability phase 2	2016-08-22	2016-08-29	329	20.4	1.46 %

Table 4.3: Ambient temperature variability during phase 2 of the test series carried out at FOI (described in section 4.1.2), including the (longer) template measurement, the full series, full series but excluding the 'lamp' provocation (see text) and the segments of the series selected as having comparatively stable temperature and comparatively highly variable temperature, respectively. A 1 % variability at a mean temperature of 20 degrees C (293.15 K) corresponds to minimum and maximum temperature in the interval being separated by 2.9 degrees.

and providing a challenge for the stabilization software to return the system to normal operation during phase 3.

4.1.3 Phase 3: Recovering Spectral Stability by Re-Engaging *VGain* Compensation

Following the testing described in the previous sub-section (without *VGain* compensation), and in particular the final stress test with direct heating by a lamp, the stabilization was switched on again for a third and final phase of the test and was operated for a final period of several weeks in gain stabilization mode. The objective was to check that the software could return the detection system to stable operation after a shock. As shown in figures 4.5 and 4.6, this was indeed the case. The centroids of the spectral position results return immediately to the template values (within 10^{-4} for the electron detectors and 10^{-5} for the photon detector).

4.2 Drift Control Software Testing in Normal IMS Operating Mode

In order to test the integration of the new software components with the latest version of the SAUNA II software under normal operating conditions, an extended series of measurements were made using the *IMS27* system at Scienta Sensor Systems. In this test, the system was in normal routine operating mode (roughly 12-hour measurements interspersed with 40-minute measurements on a QC source). The QC sources were parked in measurement position throughout the cycle rather than being introduced only during the QC measurement. This means that the test isolates the effects of spectral drift in the detectors and electronics, and the results are not affected by possible uncertainty in the repeatability of the QC source position from one measurement to another. The basic parameters of this test are summarized in table 4.4.

The template spectra were collected during 5-hour measurements that immediately preceded the test measurements. Note that in contrast to the tests at the FOI laboratory (see section 4.1) the 'test measurements' set in this case

	Start date	End date	Days	Measurements	Comments
Det A	2016-07-08	2016-08-19	42	84	Monitoring and stabilization
Det B	2016-07-08	2016-08-19	42	83	Monitoring and stabilization

Table 4.4: Summary of the test series carried out at Scienta SAUNA Systems (described in section 4.2).

include only the twice-daily 40-minute QC measurements. The ‘test measurements’ are thus separated in time by about 12 hours.

Time series of spectral positions and stabilizing gain settings during the Scienta SAUNA Systems test series are shown in figure 4.7. These results can be compared to the test at FOI using back-to-back 30-minute QC measurements (figure 4.1). Except during intermittent relatively large temperature excursions that occur in the FOI test but not in the Scienta test, the *VGain* changes required to maintain stability are somewhat larger for the IMS mode operation. The achieved precision (‘scatter’ around the template spectral position) is also somewhat worse.

The latter effect is also seen in figure 4.8 which shows histograms of the spectral positions (relative to the template spectra). The precision (RMS width of the distributions) is about 40 % worse (width about 0.7 %) for the beta channels and almost 10 times worse (width about 0.3 %) for the NaI channel. This may be due to the 12 hours elapsed time between QC measurements as compared to 30 minutes for the FOI tests.

4.3 Long Term Testing

The initial tests described in sections 4.1 and 4.2 were designed to isolate the behavior of the stability monitoring algorithm and software. In order to study the performance of a full SAUNA system running in atmospheric measurement mode for an extended time, a ‘long term’ test was carried out over a roughly four-month period (between June 9 2017 and October 20 2017). The test, including temperature conditions, is summarized in table 4.5.

	Start date	End date	Measurements	Mean temp	Temp variation
templates	2017-06-09	2017-06-09	1 (2.7 h)	20.0	0.04 %
long-term test	2017-06-09	2017-10-20	528 (each det)	22.1	1.44 %

Table 4.5: Ambient temperature variability during the long-term test (described in section 4.3), including the template measurement. A 1 % variability at a mean temperature of 20 degrees C (293.15 K) corresponds to minimum and maximum temperature in the interval being separated by 2.9 degrees.

4.3.1 Set-Up

The system hardware used for the long-term test consisted of the SAUNA III prototype developed at FOI in Stockholm (with the exception of using SAUNA II detector electronics). The software environment was SAUNA II software modified to control SAUNA III hardware, but none of the software modifications affect the spectral stability monitoring. The difference in hardware however deserves some comment.

The beta-gamma coincidence detectors differ somewhat from the SAUNA II detectors, but not in any respect that is likely to significantly influence the performance of the spectral stability monitoring. Specifically, the gas sample cells are considerably larger and different photomultiplier tubes are used for the electron detector channels. The beta-gamma spectra produced are very similar, the more so from the point of view of spectral stability monitoring since only the QC spectra are used for this purpose. The QC spectra are collected during similar time intervals (40 minutes for SAUNA II, 60 minutes for SAUNA III); the main difference is that due to the shorter sample measurement cycle of the SAUNA III the QC spectra are collected every 6 hours rather than every 12 hours as with SAUNA II. However, even for a detector with a rather large rate of 'regular' spectral drift (such as one of the detectors used in the test), the change observed from one QC spectrum to the next is of the same magnitude whether observed at 6-hour or 12-hour intervals (although it appears likely from the results reported in sections 4.1 and 4.2 that the difference between back-to-back QC measurements – effectively 30-minute intervals – and 12-hour intervals does have some influence). If, on the other hand, the drifting is not 'regular' but occurs in discrete 'jumps' it would also appear that it makes little difference whether QC spectra are collected at 6- or 12-hour intervals.

The other difference was the use of higher-precision QC source emplacement mechanisms that have been developed but not yet implemented for SAUNA II. Precision in positioning the QC source is an important factor in evaluating the results of testing the spectral drift monitoring algorithm. Tests have shown that lack of such precision can affect the spectra in a similar way as actual electronics drifting [11]. Therefore, it is believed that the improved mechanisms in fact improve the quality of the testing by isolating electronics drift as the most likely cause of any observed changes in spectra over time.

The 'master QC' spectra were collected during 160 minutes (2.7 hours) immediately before the start of the measurement series.

4.3.2 Results

Figure 4.9 shows the analyzed spectral positions relative to the template for each of the three elements, for each of the two beta-gamma detectors. Also shown are the temperatures measured at the detectors, since the initial development testing indicated a potentially large impact of temperature on detector behavior.

The two 'jumps' in position occurring in the first part of the testing period (on June 21 and on July 12) are due to software being reset for reasons unrelated to the gain stabilization software. Such resetting had the effect of re-starting SAUNA_DRIFT and SAUNA_PHDAQ with original *VGain* (default boot-time) values, which had a dramatic one-time effect on the spectra from the first measurement after re-start (a 'jump' of 9 % and 26 %, respectively, for beta 1 and beta 2 in detector A and 14 % and 25 % for detector B). As seen, however, the system promptly and successfully restored the spectral positions as soon as the next QC measurement following re-start was analyzed.

Figure 4.10 shows histograms of the spectral positions (relative to the template spectra). The precision (RMS width of the distributions) is 0.3 – 0.5 % for the plastic scintillator electron detectors and 0.09 % for the NaI photon detector. The accuracy (distance from zero relative displacement) is within about $2 \cdot 10^{-4}$ for the electron detectors and $4 \cdot 10^{-5}$ for the photon detectors. In the case of the electron detectors, the results are slightly worse (wider distributions) for detector B.

Figure 4.11 shows the evolution of the *VGain* settings as they were modified by SAUNA_DRIFT to achieve spectral stability. By the linear shift assumption underlying the algorithm (*i.e.* linear dependence of spectral position on *VGain*), this is an indicator of how the detectors would have drifted in the absence of spectral stabilization (their ‘intrinsic tendency’). Again, the correlation between temperature and drift is quite evident, particularly in the case of the NaI detectors.

4.4 Results of Testing

In summary, the tests conducted indicate that

- The algorithm that was developed works and is able to compare spectra with statistics typical of SAUNA QC measurements to a ‘template’ with slightly better statistics (several hours collection time) and determine linear shifts to a precision of better than about 1 % for the individual beta channels and better than about 0.1 % for the NaI detectors and an accuracy considerably better than 0.1 %;
- Detected shifts can be successfully corrected by predictable changes to the electronics gain;
- The software developed is stable and successfully implements the algorithm (the spectral fitting process never failed during the tests);
- The software can be successfully integrated with existing SAUNA II operational software and performed in a stable and consistent manner over more than four months operational testing;
- The cumulative effect is to retain spectral stability also over longer periods of time and also for detectors that would otherwise display considerable spectral changes;

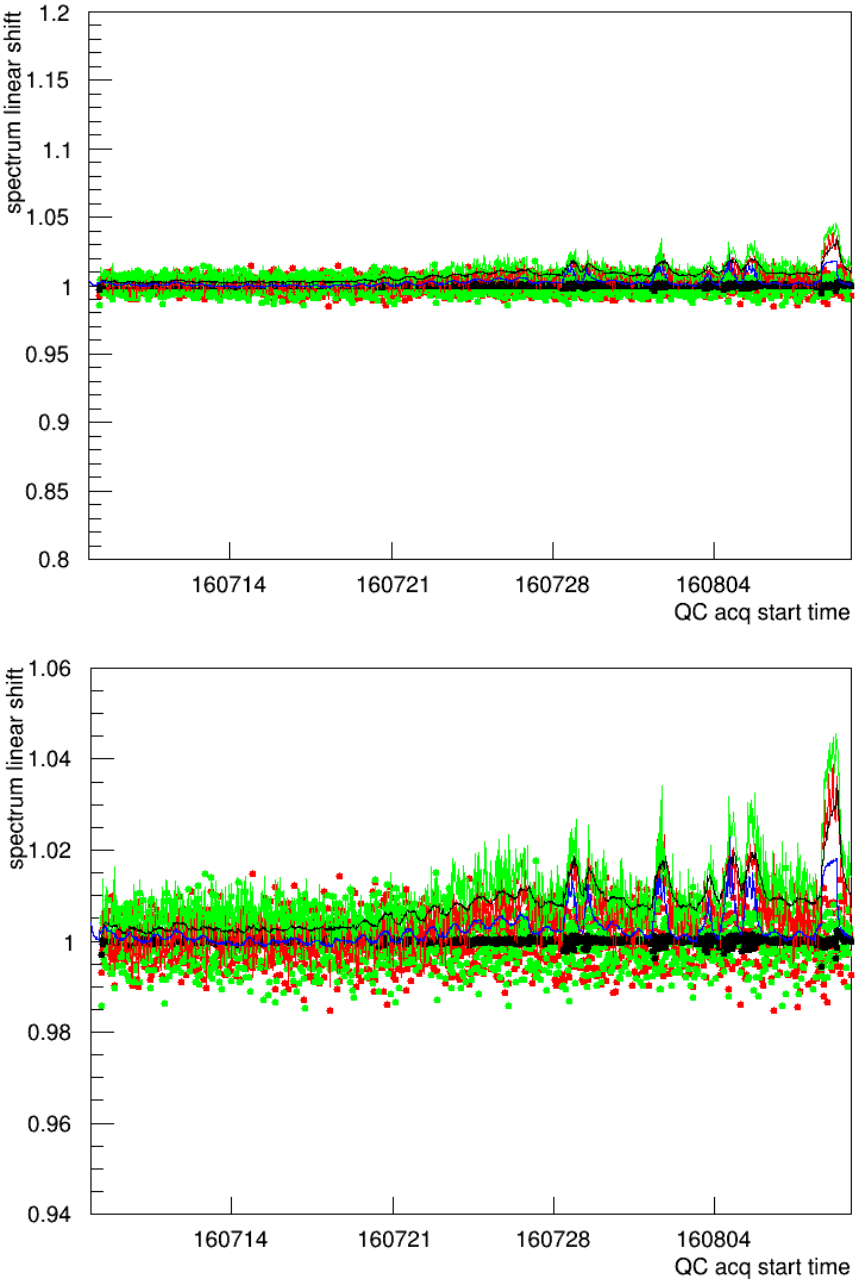
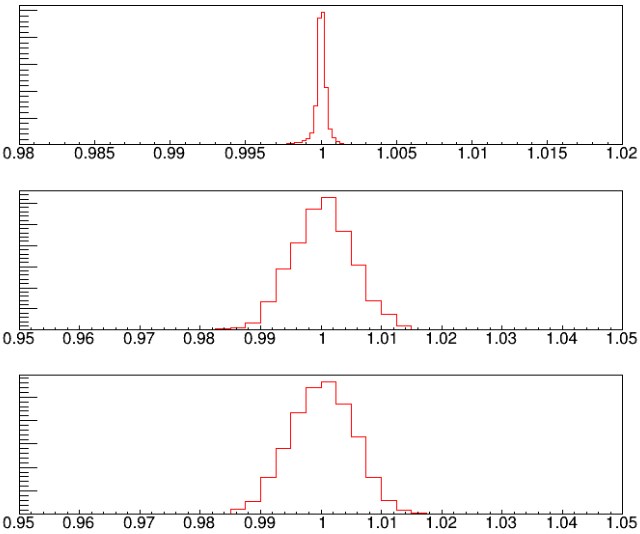
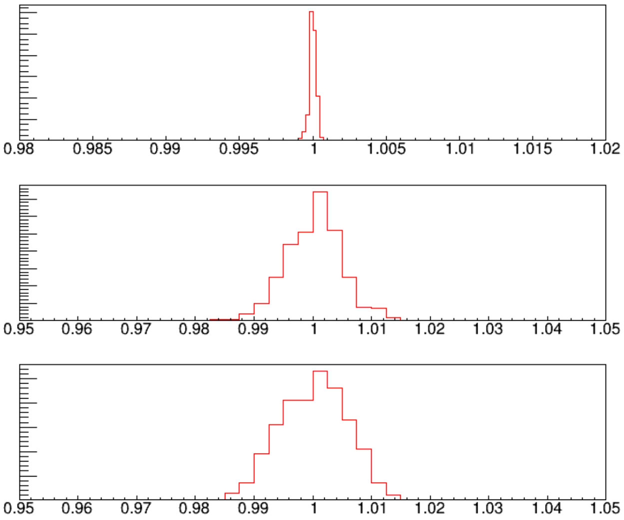


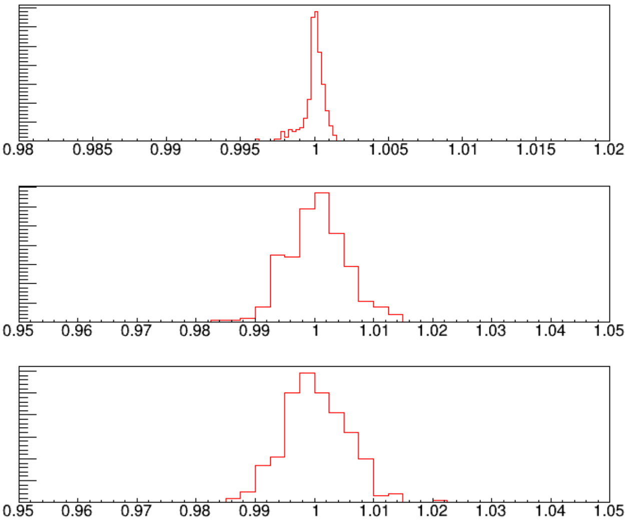
Figure 4.1: FOI test series phase 1 results. Black (NaI photon detector), red and green (electron detector PM tubes) points indicate the spectral shift determined by the software relative to the template; lines of corresponding color indicate the settings of *VGain* employed in each measurement in order to retain minimal deviation from the template. Also shown (blue) is room temperature (relative to the average temperature during the template measurement).



(a) full phase 1



(b) ‘low temperature variability’ period



(c) ‘high temperature variability’ period

Figure 4.2: FOI test series phase 1 results. Distributions of spectral position relative to template for each component (NaI in upper frame, beta 1 and 2 below).

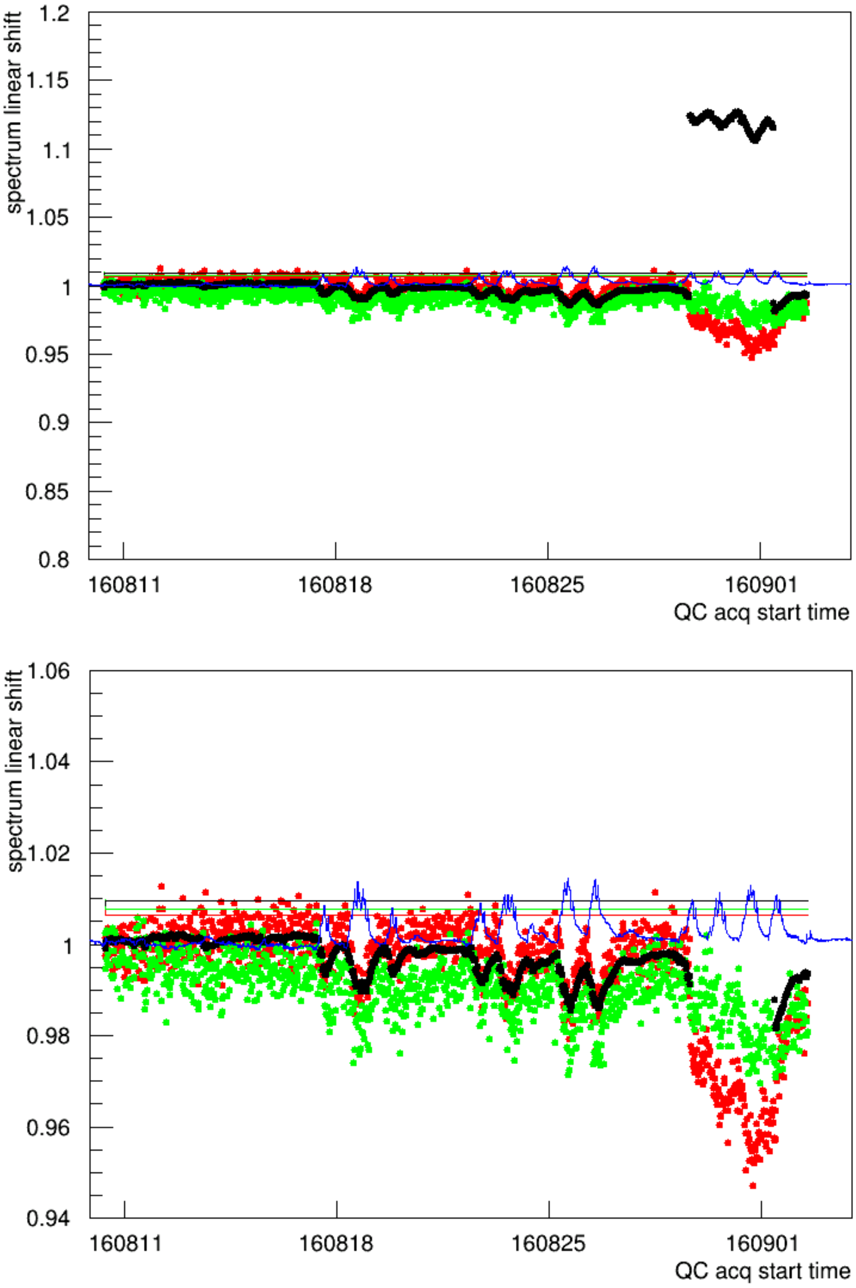
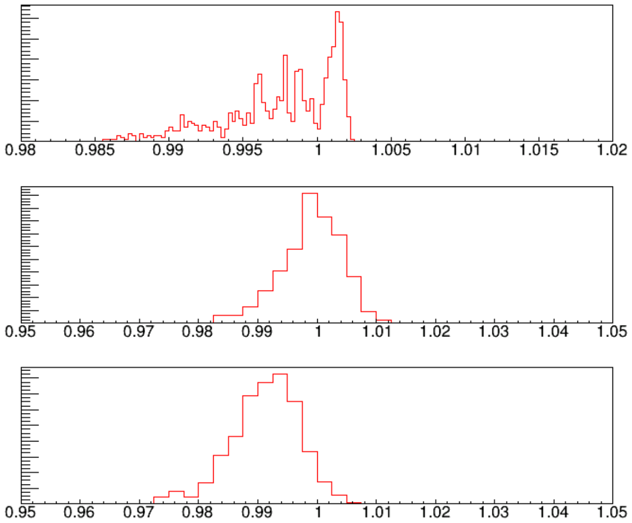
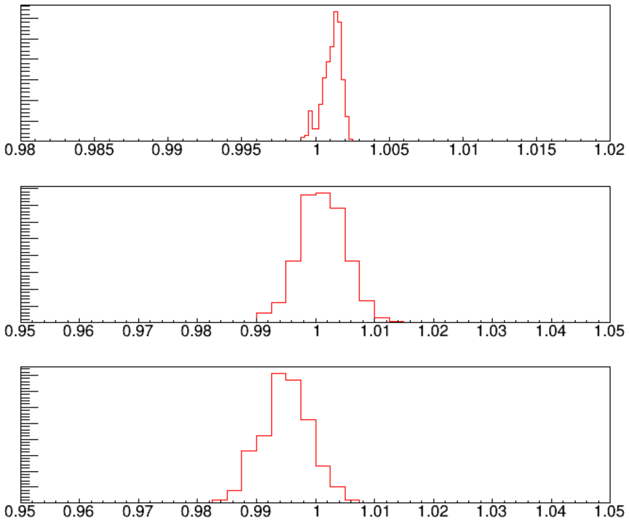


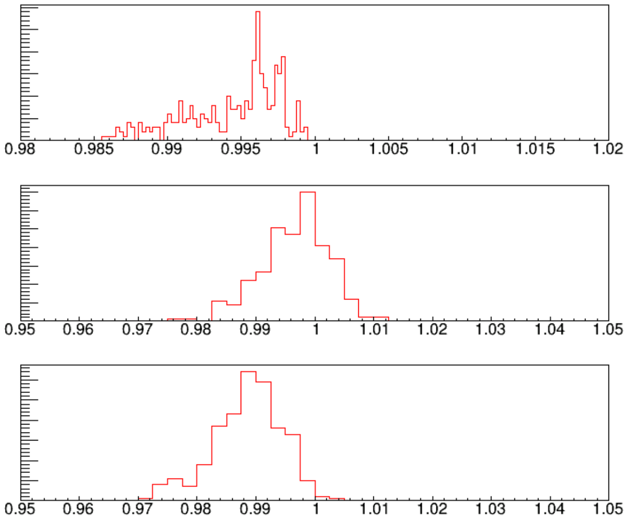
Figure 4.3: FOI test series phase 2 results. Black (NaI photon detector), red and green (electron detector PM tubes) points indicate the spectral shift determined by the software relative to the template; lines of corresponding color indicate the settings of *VGain*, fixed in this test phase. Also shown (blue) is room temperature (relative to the average temperature during the template measurement).



(a) full phase 2 except 'lamp' provocation at end



(b) 'low temperature variability' period



(c) 'high temperature variability' period

Figure 4.4: FOI test series phase 2 results. Distributions of spectral position relative to template for each component (NaI in upper frame, beta 1 and 2 below).

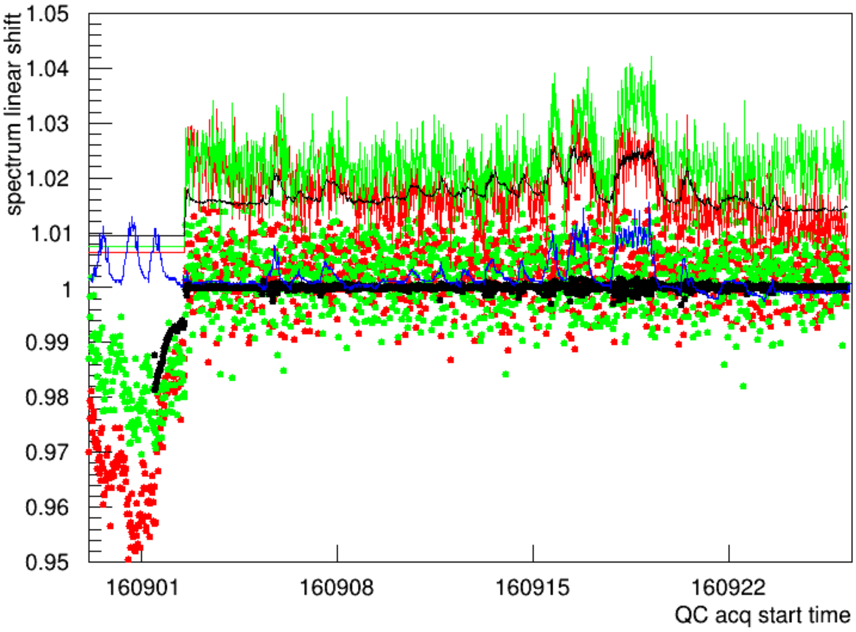


Figure 4.5: FOI test series phase 3 results (end of phase 2 also shown). Black (NaI photon detector), red and green (electron detector PM tubes) points indicate the spectral shift determined by the software relative to the template; lines of corresponding color indicate the settings of *VGain*, fixed in this test phase. Also shown (blue) is room temperature (relative to the average temperature during the template measurement).

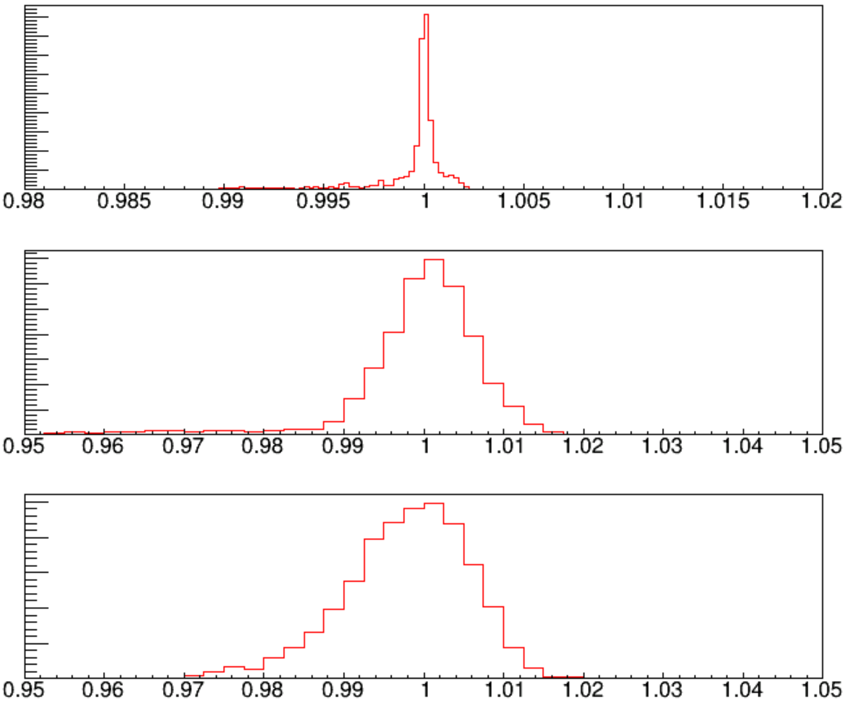
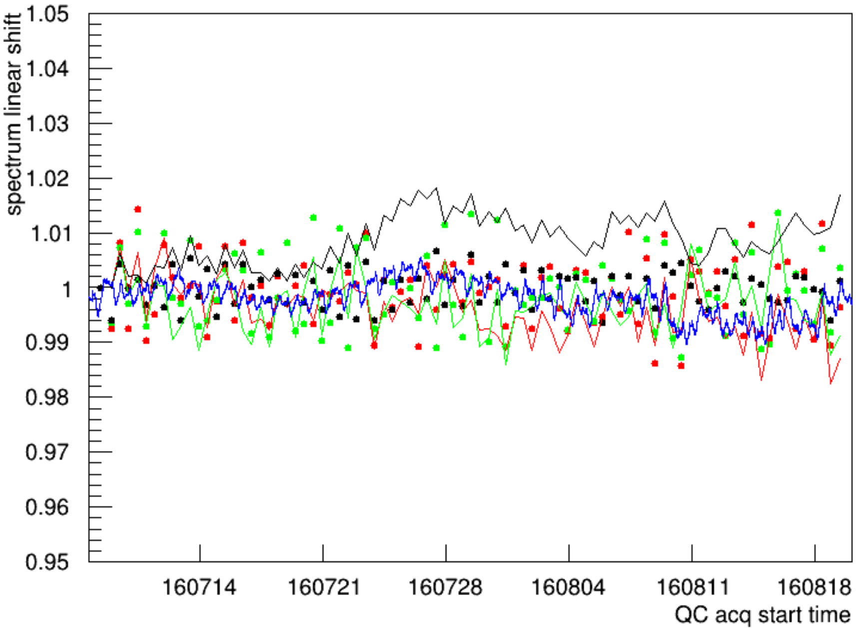
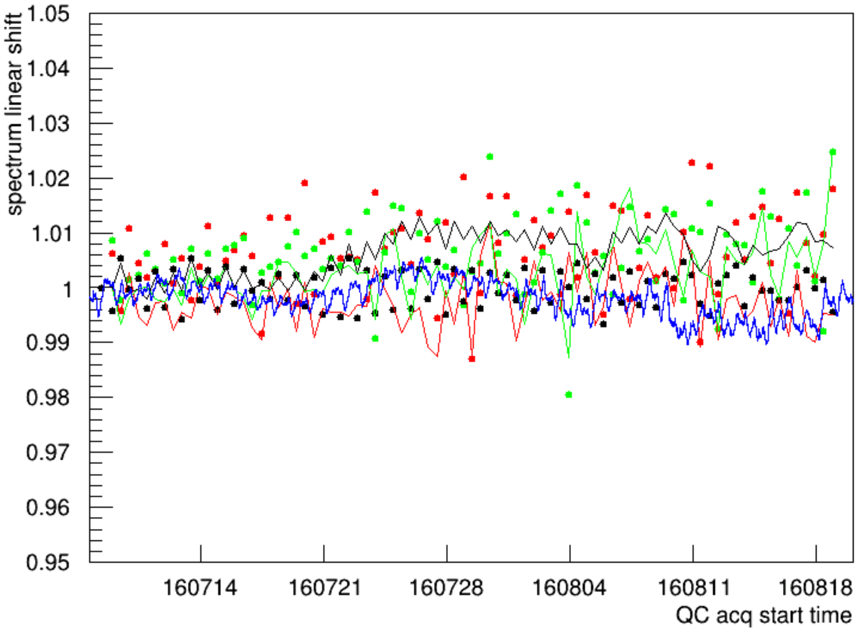


Figure 4.6: FOI test series phase 3 results. Distributions of spectral position relative to template for each component (NaI in upper frame, beta 1 and 2 below).

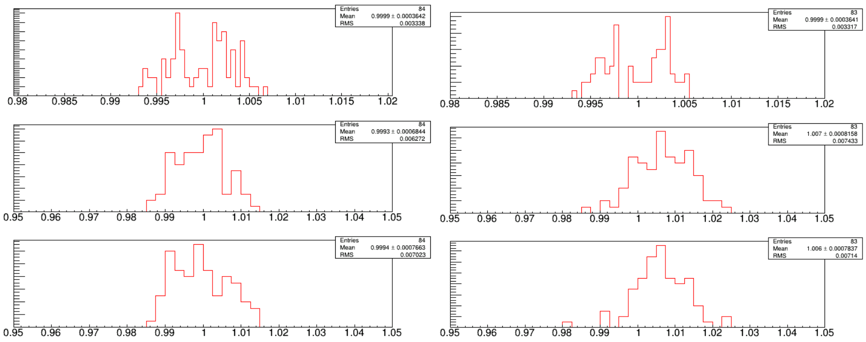


(a) Detector A



(b) Detector B

Figure 4.7: Scienta Sensor Systems test series results. Black (NaI photon detector), red and green (electron detector PM tubes) points indicate the spectral shift determined by the software relative to the template; lines of corresponding color indicate the settings of *VGain* employed in each measurement in order to retain minimal deviation from the template.



(a) Detector A (b) Detector B

Figure 4.8: Scienta Sensor Systems test series results. Distributions of relative spectral position determined by the software for each of the detector components.

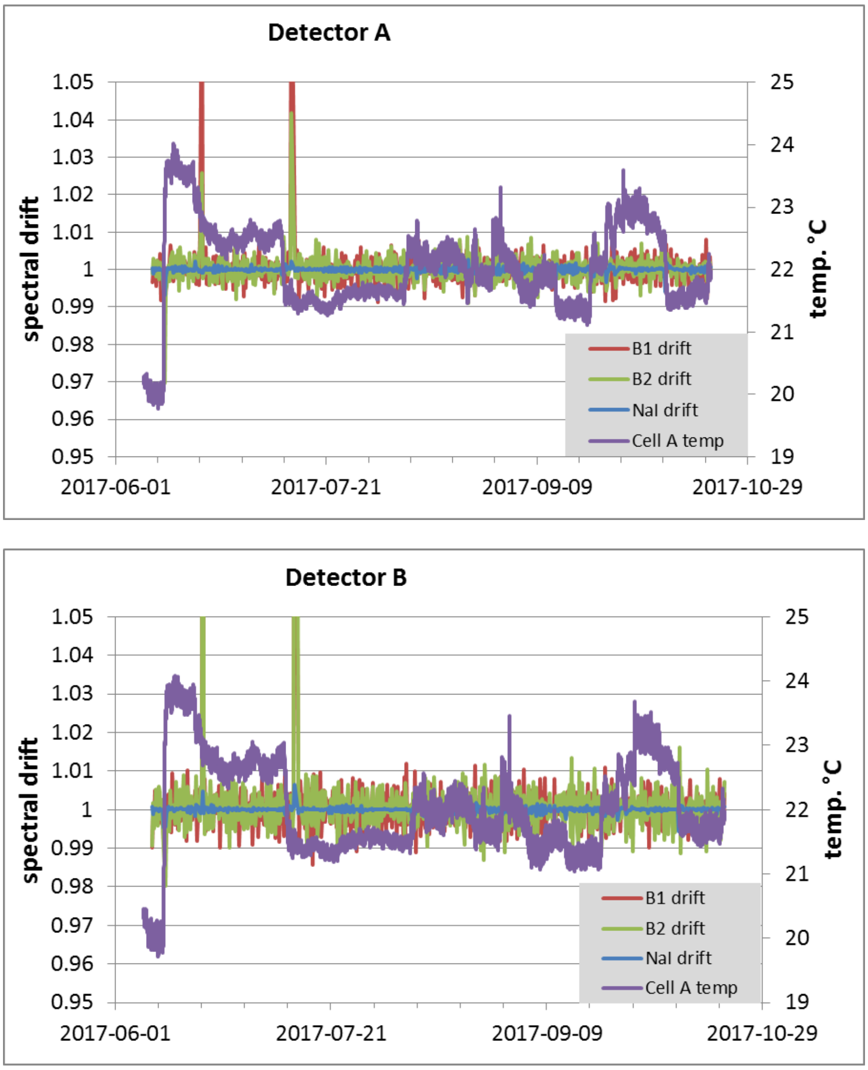
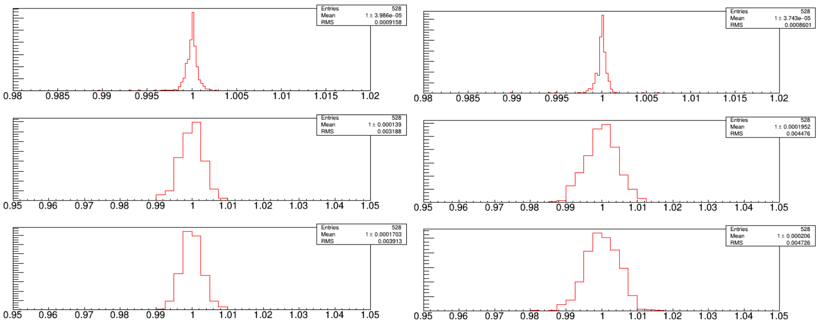


Figure 4.9: Results of long-term testing of the spectral stabilization method and implementing software using prototype SAUNA III, with new QC source emplacement mechanisms: Spectral positions over time.



(a) detector A (b) detector B

Figure 4.10: Long term test results. Distributions of spectral position relative to template for each component (NaI in upper frame, beta 1 and 2 below).

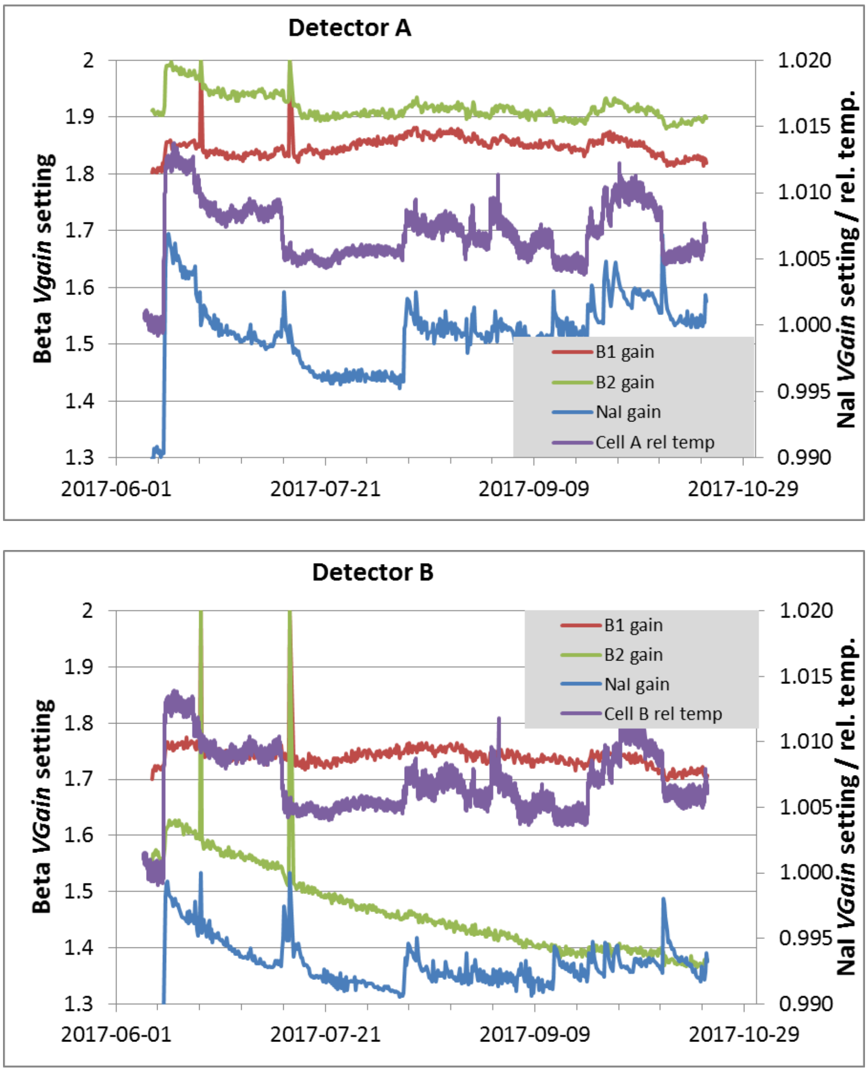


Figure 4.11: Results of long-term testing of the spectral stabilization method and implementing software using prototype SAUNA III, with new QC source emplacement mechanisms: Compensating *VGain* settings over time.

5 Incorporation of Drift Correction Output Into IMS Data Formats

As described in chapter 3, the output from the spectral stability monitoring and correction is written to appropriate tables in the SAUNA on-board database. Suitable elements of this output can be incorporated into system output in the form of entries in the appropriate data files produced. This chapter contains suggested modifications to the IMS data formats to accommodate the needs of data users with regard to the spectral stabilization.

The changes suggested below have not yet been incorporated in the SAUNA system software.

5.1 Template Measurement

In addition to suggested data format changes (presented below), provision should also be made for distribution and handling of the measurement used as template for the stability monitoring. Obviously, it is best if this spectrum represents the state of the system at the time of energy calibration and determination of analytical regions of interest. This corresponds to the ‘master QC’ spectrum generated first in the recommended SAUNA calibration procedure [12, 13]. In any case, the IMS “data type” of this measurement data should be “CALIBPHD” and the “measurement identification” (MID, according to the IMS2.0 format documentation [14]) would be used to refer to it when needed.

5.2 Pulse Height Data

The IMS2.0 format specifications for the various pulse height data (PHD) data type files should be augmented with a ‘#Gaincorr’ data block containing the information shown in table 5.1 (adopting the style of the IMS2.0 format documentation [14]):

Record	Position	Format	Description
1	1-9	a9	#Gaincorr
2	1-31	a31	template MID
	33-63	a31	monitored MID
3	1-3	a3	NaI flag
	5-43	a39	NaI gain correction statement
4	1-3	a3	Beta 1 flag
	5-43	a39	Beta 1 gain correction statement
5	1-3	a3	Beta 2 flag
	5-43	a39	Beta 2 gain correction statement

Table 5.1: Suggested new ‘#Gaincorr’ data block format for PHD type data messages.

In table 5.1, the “template MID” and “monitored MID” are, respectively, the measurement identification codes [14] for the ‘master QC’ measurement used as a template and the relevant (see below) QC measurement that was compared to it to determine any gain drifting.

The 'monitored' QC measurement that is relevant for the measurement being reported in the current file (the 'current' measurement) is the one that was followed by a gain drift analysis that resulted in the *VGain* settings that were in force during the 'current' measurement. This measurement must be located by the report-generating software from the contents of the SAUNA database. The *Acquisition* table contains one row for each measurement containing the information needed: start and stop times, *VGain* settings during the measurement and, for QC measurements that were analyzed for gain drifting, the result of the analysis in terms of the spectral shifts relative to the template and the degree of success in the analysis (see section 3.4). The relevant 'monitored' QC measurement should have *VGain* settings that are related to the *VGain* settings of the 'current' measurement such that the ratio of each *VGain* for the two measurements equals the corresponding shift (since the change in *VGain* settings was applied after conclusion of the relevant 'monitored' QC measurement). The relevant 'monitored' QC measurement should also be a recent one, so that it is reasonable to assume that no significant spectral drift occurred between that measurement and the 'current' measurement.

Several different outcomes of locating a relevant 'monitored' QC measurement can be imagined:

1. In normal SAUNA operation with SAUNA_DRIFT running, the relevant 'monitored' QC measurement will be found to be the immediately preceding measurement for the same detector.

   In addition, several circumstances that are not 'normal' may be imagined:

2. The most recent QC measurement has no SAUNA_DRIFT-related entries in the *Acquisition* table (*i.e.* no analyzed shift and no analysis success/-failure flags). This could happen if SAUNA_DRIFT was not running at the time of the QC measurement. In this case, the "monitored MID" field in record two should be left empty.

3. One or more *VGain* setting(s) of the most recent QC measurement do(es) not correspond to the product(s) of the corresponding determined shift(s) and *VGain* setting(s) for the 'current' measurement even though the corresponding **CorrFlag* word (see table 3.3) indicates that gain correction was successful (bit 7 not set). This could happen if SAUNA_DRIFT performed the drift analysis, but was not set to request an actual corresponding change of *VGain* setting(s) (the *DRIFTCORR_** word(s) set to zero in the *Configuration* table). Less likely, it could happen if, for some reason, the *VGain* setting(s) were changed by some agent other than the SAUNA_PHDAQ-SAUNA_DRIFT interaction described in this report.

4. A QC measurement is found with the right gain shift analysis outcome to *VGain* settings relationship, but it is not 'recent'.

The rest of the '#Gaincorr' data block should be populated based on the outcomes above:

For case 1, the three-digit "flags" in records 3 – 5 are the respective **CorrFlag* words described in table 3.3 as read from the *Acquisition* table of the system database for the relevant 'monitored' QC measurement. The "gain correction statements" will be either the statement "NO *XX* gain correction performed" or the statement "*XX* gain correction performed", where *XX* identifies the detector element that the statement refers to (*i.e.* one of "NaI", "Beta 1" or "Beta 2"). This statement would be made on the basis of whether bit 7 in the respective "flag" is set or not.

For case 2 (with no identified relevant 'monitored' QC measurement), the flag digits should be set to "128" (*i.e.* bit 7 but no other bits set), indicating the absence of any SAUNA_DRIFT action, since the service by itself does not set bit 7 of the **CorrFlag* word for an acquisition unless one or more of bits 0, 2, 4 and 6 are set. The "gain correction statements" will be the statements "NO *XX* gain shift analysis found" (with *XX* signifying each of the elements "NaI", "Beta 1" or "Beta 2") .

Case 3 (one or more gain shift analyses not current or not implemented as corrections) should result in a flag value equal to the **CorrFlag* word with 128 added (to set bit 7). The "gain correction statement" for detector element *XX* will be the statement "*XX* gain correction NOT CURRENT"

Finally, case 4 should be treated like case 1, but the statement "*XX* gain correction performed" should be augmented to become "OLD *XX* gain correction performed" as a warning that a non-'recent' correction was used.

It is suggested that parsing each bit of the flags (see table 3.3) and writing all the corresponding messages in the '#Gaincorr' block would be of little utility to most recipients of data messages, and would yield an unnecessarily cluttered format. Simply stating whether or not gain stabilization was performed should be sufficient (in addition to providing the entire flag in bit-encoded form).

The current version of the software implementation has no way to indicate on a per-measurement basis (*i.e.* in the *Acquisition* table) whether the SAUNA_DRIFT service, at the time of measurement, had been instructed to request gain changes or not (*i.e.* whether the *DRIFTCORR_** words in the *Configuration* table were non-zero or not – see section 3.3). If SAUNA_DRIFT was running, gain shift analysis would have been performed and results recorded. If the *DRIFTCORR_** words were set, no change in the *DETECTOR*_NEXT_VGAIN_** parameters would have been executed, regardless of the result (success or failure) of the analysis. As noted above, by comparing the values of the **_VGain* and **Drift* parameters set during the relevant 'monitored' QC measurement to those for the 'current' measurement, it is still possible to determine whether gain correction was enabled or not. However, this could be a cumbersome and error-prone procedure. Most probably the best remedy is to introduce another bit in the **CorrFlag* words (bit 8), indicating by a SET status that the corresponding *DRIFTCORR_** word was non-zero and treatment exactly as described above. A non-set status would indicate that the corresponding *DRIFTCORR_** word was zero, which should lead to a new statement "*XX* gain correction TURNED OFF" or similar.

5.3 State of Health Data

The IMS2.0 format specifications for state of health (RMSSOH) data type files should be augmented by a new data block '#Gainstab' to record the parameters **CorrFlag* (spectral shift analysis success/failure status) and the parameters **Drift* (analyzed spectral shift between the 'template' and 'monitored' measurement). See section 3.4 and particularly table 3.2 for details concerning these parameters. Furthermore, the *VGain* settings on the system should be defined as *ProcessSensors* SOH data. The following sub-sections provide details on the suggested formats.

5.3.1 New RMSSOH Data Block '#Gainstab'

The new '#Gainstab' data block would record each gain shift analysis as it occurs, in terms of measurements compared (template and "monitored") and results. The updating would be similar to the "#DetEnv" or "#PowerSupply" blocks, with entries only for each new analysis (which would occur every time SAUNA_DRIFT detects a new QC measurement). There would be no need for regular updates between gain shift analyses. The suggested format is shown in table 5.2.

Record	Position	Format	Description
1	1-9	a9	#Gainstab
2-n	1-31	a31	template MID
	33-63	a31	monitored MID
	65-67	a3	NaI flag
	69-75	f7.4	NaI drift
	77	a1	NaI gain correction (1) or not (0)
	79-81	a3	Beta 1 flag
	83-89	f7.4	Beta 1 drift
	91	a1	Beta 1 gain correction (1) or not (0)
	93-95	a3	Beta 2 flag
	97-103	f7.4	Beta 2 drift
	105	a1	Beta 2 gain correction (1) or not (0)
	107-116	i4,a1,i2,a1,i2	date (*yyyy/mm/dd*)
	118-127	i2,a1,i2,a1,f4.1	date (*hh:mm:ss.s*)
	129-134	i6	SOH data sampling interval duration (s)

Table 5.2: Suggested new "#Gainstab" data block format for RMSSOH data messages.

In table 5.2, the "template MID" and "monitored MID" are the measurement identification codes for the two measurements compared in the analysis. The "flags" are the **CorrFlag* words from the *Acquisition* table entry for the "monitored" QC measurement (see table 3.2). The "drift" entries are the **Drift* entries from the same row (which represent the fractional change in the spectral positions). For each detector element (NaI, beta 1 and beta 2), there is also an entry that reflects whether SAUNA_DRIFT was actually instructed to implement gain changes in response to the analyses (1) or not (0). This information should come from the status of the corresponding *DRIFTCORR_** words in the *Configuration* table (see table 3.1).

5.3.2 New *ProcessSensors* SOH Data

The settings of the *VGain* parameters on the system should be recorded as *ProcessSensors* data. There are three such parameters for each detector (one each for NaI, beta 1 and beta 2). The parameters are dimensionless, and do not correspond to any of the sensor types defined in the existing formats [14]. Ideally, a new sensor type *GAIN* should be defined. However, one of the already defined types might also be used as a proxy.

The values may in the general case be obtained by SAUNA_PHDAQ directly querying the Pixie4 electronics for the current value at any time. Currently, however, they are only used in the context of spectral stabilization on a per-measurement basis, and are stored, for each measurement, in the *Acquisition* table of the SAUNA system database. Suggested parameter names are "*XXddd*_VGain", where "*XX*" represents one of "NaI", "Beta1" or "Beta2" and "*ddd*" represents the three final digits of the "detector code" as defined in [14].

6 Concluding Status and Suggested Further Developments

A method to automatically determine fine spectral differences in SAUNA beta-gamma detector systems has been developed. The method has been implemented in an extension to the SAUNA software to perform a comparison of the QC spectrum preceding each sample and gas background measurement with a 'master QC' spectrum. The result is an adjustment of the electronic gain before each such measurement in order to maintain spectral stability over time.

The algorithm and the software extension have been tested at FOI and at the SAUNA system manufacturer to ensure both the soundness of the algorithm and the stability of the software. No operational or software stability issues have been noted during the course of the testing. Spectral stability, defined as consistency with the 'master QC' spectrum, is achieved with a precision of better than 1 % for beta pulse height spectra, and approximately a factor 10 better than that for NaI photon energy spectra.

The method developed can be implemented on both the current SAUNA II system and on the SAUNA III system currently in advanced development. Variations in QC source placement can affect spectra in a similar way as detector gain changes. Obviously, modifying the gain in response to spectral changes that are in fact caused by another factor would be undesirable. Therefore, the gain stabilization developed in this work should be implemented only in conjunction with installation of the new, more precise QC source emplacement mechanism used in the long-term testing (see section 4.3).

Input and output from the spectral stability monitoring is via the SAUNA on-board database. Relevant parts of the information stored can be provided to end-users in the form of extensions to the pulse-height data and state of health messages sent by the system. Suggested extensions to the formats have been developed, but have not been implemented in the SAUNA messaging software.

In the course of software development, testing and formats development, some points have emerged that could be addressed in further development:

1. Extend the analysis status flags (**CorrFlag*) words (section 3.4) with an additional bit 8, indicating by a SET status that the corresponding *DRIFTCORR_** word (in the *Configuration* table) was non-zero (change of gain to be requested in response to spectral shift analysis) and by a non-set status that the corresponding *DRIFTCORR_** word was zero (no change of gain to be requested).'

2. The original design of the software included a provision for not executing gain changes if the accumulated gain change over time had exceeded some limit, or if the gain change in any one step exceeded some limit. However, in view of the testing results reported here (chapter 4), which indicate a quite stable and reliable behavior despite sometimes rather dramatic changes in detector behavior (see *e.g.* figures 4.1 and 4.9), it was decided not to implement any such limitations at this time. Any dramatic analysis failure should result in the appropriate flag being generated (see section 3.4), which should prevent the execution of a corresponding gain change in any case. Should there be any need to reconsider this decision in the future, it would be a straightforward matter to limit the size of

VGain correction that the software is allowed to make. This would also imply that the software should generate an alarm but not execute any gain change if the limit is exceeded.

3. In the present implementation of SAUNA_DRIFT, the original gain is applied after a power outage or software restart. This should be changed such that the most recent successfully determined gain value is used instead.
4. Previously, there has been no way to confirm the proper operation of the QC source emplacement mechanism before actions are taken based on the data collected. The new QC hardware offers the possibility to provide feedback to the software whether the QC source was indeed correctly moved into or out of the detector. This information could be reported in the IMS file and could also be used by the software to decide whether a drift correction should be performed or not.

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