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Portable spectrometer for ionizing radiation „Gammamapper“

VELJO SINIVEE

TUT PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
Faculty of Science
Department of Physics

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Supervisor:
Prof. Rein-Karl Loide, Department of Physics, Faculty of Science, TUT

Opponents: Dr. phys. Alberts Kristins, University of Latvia, Riga, Latvia
Dr. phil. Madis Kiisk, University of Tartu, Estonia

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

Veljo Sinivee

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Portatiivne ioniseeriva kiirguse spektromeeter „Gammamapper“

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List of publications

This thesis is based on the following papers, which have been referred to in the text as Article I till Article VI.

I. Sinivee, V. (2006). A Simple Data Filter for the GPS Navigator. Instruments and Experimental Techniques, 49(4), 511 - 512.
II. Sinivee, V. (2007). A prototype gamma spectrometer-datalogger binds data to geographical coordinates and offers protection of measurement results. In: Innovative Algorithms and Techniques in Automation, Industrial Electronics and Telecommunications: CISSE 2007, detsember 2007, elektroonne konverents. (Edit.) Sobh, T.; Elleithy, K.; Mahmood, A.; Karim, M.. Springer, 2007.
III. Sinivee, V.; Kurik, L.; Kallavus, U. (2008). Combined Positioning System for Mapping Measured Properties of Objects of Arbitrary Shape. Küttner, R (Toim.). Proceedings of the 6th international conference of DAAAM Baltic industrial engineering, 24-26th april 2008, Tallinn, Estonia (183 - 188). Tallinn: Tallinn University of Technology.
IV. Sinivee, V.; Kurik, L.; Kallavus, U. (2008). Mobile Photogrammetry for positioning measuring sensors. In: BEC 2008 : 2008 International Biennial Baltic Electronics Conference : Proceedings: 11th Biennial Baltic Electronics Conference, Tallinn University of Technology, October 6-8, 2008, Tallinn, Estonia. (Toim.) Rang, T.. Tallinn: Tallinn University of Technology, 2008, 227 - 230.
V. Sinivee, Veljo (2007). A Device for Remote Control of an Experiment via E-mail. Instruments and Experimental Techniques, 50(4), 494 - 498.
VI. Sinivee, V. (2008). Simple yet efficient NMEA sentence generator for testing GPS reception firmware and hardware. In: Innovative Algorithms and Techniques in Automation, Industrial Electronics and Telecommunications: CISSE 2007, detsember 2007, elektroonne konverents. (Edit.) Sobh, T.; Elleithy, K.; Mahmood, A.; Karim, M.. Springer, 2008.

Contents

1. Introduction

Ionizing radiation sources can be found in a wide range of occupational settings including health care facilities, research institutions, nuclear reactors and their support facilities, nuclear weapon production facilities, and other various manufacturing settings just to name a few [5, 40]. These radiation sources can pose a considerable health risk to affected workers if not properly controlled.

From the point of view of the occupational exposure, the radiation dose is a very important measure. On the other hand, limiting only to measuring dose, like it is done in many industrial dosimeters does not necessarily give enough information about possible hazards. For example safe dose of ^{137}Cs in one litre of drinking water is 1 kBq, dose for ^{239}Pu on the other hand is only 1 Bq [5]. The second isotope is 1000 times more dangerous. It is not possible to determine isotopes with a dosimeter [20]. Questions like which isotopes cause the radiation, is the source in liquid state, could it cause contamination of water, does it accumulate in tissues etc are best answered by measuring the energetic spectra of the radiation source under investigation.

In professional spectrometers energy of gamma particles fallen into sensor is measured and stored into channels. Depending on instruments design, rapid changes in radiation level can be filtered out. So moments of quickly passing a highly active material can be left unnoticed.

In case of recording every pulse output by the radiation detector, even short bursts can be found and analyzed. This method might not be very practical when investigating a highly active source since it produces too much data. Environmental research is different.

When studying environmental radioactive pollution, it is essential to have the measurement data bound to geographic coordinates. This could be done by measuring in places with known coordinates. Better, more exact and convenient way is to use a GPS-receiver. Modern GPS-engine is a handy tool, especially convenient if the data should be collected from a moving vehicle.

Combining geographic coordinates and energy of gamma particles allows building a radiation map. Also the nature of the process how ordinary man collects radiation doze can be studied and even geographic maps characterizing distribution of ionizing radiation could be constructed. Building a device for such study was the main goal of the present work.

Present thesis describes a prototype gamma spectrometer-data logger called “Gammamapper” designed, built and tested by the author of present work. This device is equipped with a CsI(Ti) scintillator probe and spectroscopic amplifier from Scionix. Every pulse output by the amplifier is captured by a peak detector, digitalized and stored on a memory card. Instrument's main processor tracks and stores geographic coordinates received by GPS engine and pre-filtered by a separate low-power microcontroller that is looking for certain messages only. This “filter” also keeps track on the validity of geographic data and double-buffers it [Article I].

The main processor of the spectrometer protects measurement results by encrypting data [Article II].

The structure of the present thesis is as follows. In the third section an overview of existing industrial gamma spectrometers similar to the present design is given. Then a block-diagram explaining work of “Gammamapper” is discussed.

In the 4-th and 5-hs paragraphs the construction of the instrument is described in greater detail. These sections are relatively long and important since they deal with author's work: designing a portable gamma spectrometer. The 6-th section of present thesis is mainly concentrated on software which was also authors concern and headache during numerous sleepless nights... More interesting parts of spectrometer's firmware and an analysis tool written for a standard PC are discussed.

The 7-th section is concentrated on Gammamapper's properties. Test measurements and spectra gathered by author thus far are also analyzed.

Acknowledgements

I would like to begin by expressing my sincere gratitude to my parents, especially my father who fostered in me a deep interest in science and technology always inspiring and impressing me by his encyclopedic erudition and unreserved support in my undertakings.

My supervisor, prof. Rein-Karl Loide has become an example of a scientist for me towards which I’m trying to tend. He introduced me to the topics of radiation measurements and then provided me with necessary freedom for fulfillment of my scientific research interests.

My colleague Lembit Kurik was extremely helpful with valuable ideas and suggestions. Lembit is a rare case since his knowledge in physics is strongly linked to practice

I would also like to express warm thanks to my colleagues from the department of Physics and also to friends from the department of Electronics who, without any doubt, gave me access to costly equipment that I did not have.

Finally, I’d like to address special thanks to my lovely wife who inspired me in this work and understood why in time of searching for solutions to “Gammamapper” I could not pay her all the attention she undoubtly deserves.

2. List of abbreviations

ADC – analog to digital converter
BLR – base-line restorer
DAC – digital to analog converter
FAT – file allocation table
FET – field effect transistor
GPS – global positioning system
GUI – graphical user interface
HP – high purity
MCA – multichannel analyser
OPAMP – operational amplifier
RAM – random access memory
USB – universal serial bus
μP – microprocessor

3. Existing portable gammaspectrometers and MCA-s for ionizing radiation.

Portative spectroscopic systems were relativelty rare when author started about 10 years ago his research work in the field of building such instruments. The majority of instruments were large and expensive although possessed excellent resolution. Naturally there are also smaller devices like the ones mentioned in [10,11,12,33,36] but high-resolution detector implemented in some designs needs cooling with liquid nitrogen. Use of such systems in field was and is difficult if not impossible. One exception to this tendency was MCA-8000 of Amptek Inc [34]. Company's multichannel analyzer was one of the early birds in field of portable and autonomous gammaspectroscopy instruments. MCA-8000 is unfortunately an MCA only. Experimenters still have to use a separate (gamma-) sensor and corresponding spectroscopic amplifier. Detectors usually need to have a powerful supply which might complicate using the system in field measurements.

The MCA of Amptek itself only gathers and stores gamma information. A personal computer is needed to download data from the instrument and run various analysis tools. Since many devices manufactured by Amptek are used also by NASA in space exploration, price of MCA-8000 is in the same scale (about $12.000).

Applications for ionizing radiation are wide. One interesting application is neutron activation analysis [3,6,15,16] which is used in archeology, biochemistry, environmental monitoring etc. Spectroscopic system must be equipped with a high resolution detector for that kind of analysis.

People involved in handling radioactive materials would need an instrument capable of acquiring high quality spectra of ionizing radiation in field conditions. Spectrometer should be a compact, autonomous, low-power device capable of displaying results in graphical form on the fly or at least right after measurements are completed, preferrably on the built-in display of the device. Environmental research applications would also need coordinates of measurement place to be recorded. Additionally, the device should be small enough to fit into a shirt pocket. Audible alarms presettable for different energy ranges are desirable. Instruments having all mentioned capabilities did not exist when present the research work was started.

The need for a somewhat better instrument still holds although there are many spectrometers with graphic display of results on market nowadays. Some Geiger counters even use a GPS engine [17]. Unfortunately a Geiger-Mueller tube does not reveal energetic contence of detected radiation. Thermoluminescent devices are compact but results could be viewed only after special processing. Last but not least – designed device should have a competitive price. Analyzing properties of existing industrial instruments (see table 3.2 and literature sources [10,11,12,33,34,36,38]) I tried to determine optimal number of channels and other relevant parameters of instrument to be designed.

Typical multichannel analyzer of a spectroscopic system has 256 to 16384 channels (see table 3.2). This number depends of type of gamma detector connected to the system. Generally a sensor with better resolution needs an MCA with more channels (this translates to an ADC with better resolution) [14,35]. A bigger number of channels is also needed if the device should work in wider energy range (see table 3.1) [14].

Table 3.1. Properties of selected gamma sensors

Detector type	**Typical resolution**	**Optimal energy range**	**Number of channels**
NaI(Ti)	8% (52keV)@662 keV; 31 keV @ 122 keV	2…200 keV	**512 or 1024**
CdZnTe	1,5 keV@122keV; 6,4 keV@662 keV	0…1 MeV	**2048…16384**
Si (Li)	180 eV @ 5,9 keV	2…100 keV	**512 or 1024**
HPGe	0,5 keV @ 122 keV	5…2000 keV	**2048…16384**
HgI_2	1,5 keV @ 5,9 keV	2… 60 keV	**2048…16384**

Table 3.2. Parameters of some industrial designs. Remarks: 1 – if connected to a computer, 2 – for the MCA only, 3 – depends on the number of channels which is selectable

Name	Manufacturer	Nr. of chan-nels	Dynamical nonlin-earity	Integral nonli-nearity	Nr. of spec-tra	Max. nr. of ROI-s	Automatic energy calibra-tion	Identifi-cation of iso-topes	Calcula-tion of activity
Easy-Spec	Canberra Indust.	1024	±1 channel	±0,3%	≤ 90	≤ 5	+	+	+
NaI Inspec-tor	Canberra Indust.	2048	±0,9%[2]	±0,025%[2]	?	?	+ [1]	+ [1]	+
Explo-rer	American Nuclear Systems.	256	?	?	60/256	4	?	?	?

MCA-465	TCA-Systems	256	?	?	14	?	?	+	?
Pros-pector	American Nuclear Systems.	4096	±3%	±0,1%	?	64/256	?	?	?
MCA-8000	Amptek Inc.	16384	±0,6%	±0,02%	128[3]		+[1]	+[1]	+

An MCA built for a semiconductor-based detector (i.e. HP Ge) would have too much channels for use in conjunction with a wide-spread lower resolution NaI detector. Too big a resolution makes finding peaks with lower energy difficult in a spectra of a high-enery source [14]. Analyzer MCA-8000 overcomes this problem using programmably selectable resolution [12]. This workaround also helps saving the memory space of the instrument for storing more spectra. Since the device stores all data into onboard RAM with relatively small capacity, this could be an issue.

Data in tables 3.1 and 3.2 suggests using a NaI sensor. The choice is logical since sensitivity of this type of detector is very high although resolution of NaI detector is moderate.

Work in field conditions dictates using a ruggedized construction and nonhygroscopic sensor. This requirement leads to using a CsI(Ti) detector [29] like the one manufactured by Scionix. CsI(Ti) detectors have similar properties to NaI(Ti) counterparts but are nonhygroscopic and more reliable. The sensor of Scionix has many attractive features like low power consumption, small size and built-in spectroscopic amplifier. Detector incorporates also a temperature sensor. Author selected for his gamma spectrometer sensor 20P25/18-E2-C-X of Scionix.

Due to CsI(Ti) -sensor's moderate energetic properties resolution of ADC in instruments signal path may be limited to 10-bits. Described ADC-s are on-chip in many common microcontrollers. Built-in ADC helps reducing board space and system price. Usually they also consume less power.

Many of the devices in table 3.2 use relatively low-capacity internal data storage. Spectrometer designed in present work should be capable of acquiring and storing data continuously for at least 8 hours. This requires a much bigger memory device. Author used a cost-effective and handy storage device capable of storing large amounts of data – a standard memory card.

The majority of instruments in table 3.2 implement a monochrome display. Geographic maps or ionizing radiation spectra would look much more compendious when displayed on a color display. Modern techniques makes using large color displays possible and even simple.

3.1. Prototype of autonomous portable gamma spectrometer – "Gammamapper"

The spectrometer uses Scionix's off-shelf gamma sensor V10P25/10-E3-Cs-T-X (1) with built-in spectroscopic amplifier (see figure.3.1). This CsI(Ti) probe has compact size, improved ruggedness, is non-hygroscopic and has significantly lower power consumption as compared to standard designs implementing NaI(Ti) scintillation detectors and PMT tubes. Scionix's state-of-art sensor provides a bipolar semi-gaussian output signal with total pulse duration of 15 μs (peaking time is 2 μs). Energy resolution measured at 662 keV is 8,7% [29].

Sensor's output pulses are fed to a peak-detector (2) built around fast operational amplifiers by Analog Devices [32]. Detector is reset after every successive digitalization of input pulse.

Successive approximation type analog to digital converter (3) converts captured pulse's amplitude to digital form. This signal is handled by unit's controller.

Measuring process is controlled and all necessary conversions are carried out by firmware running on a standard off-shelf microcontroller, manufactured by Microchip. This microprocessor has low power consumption

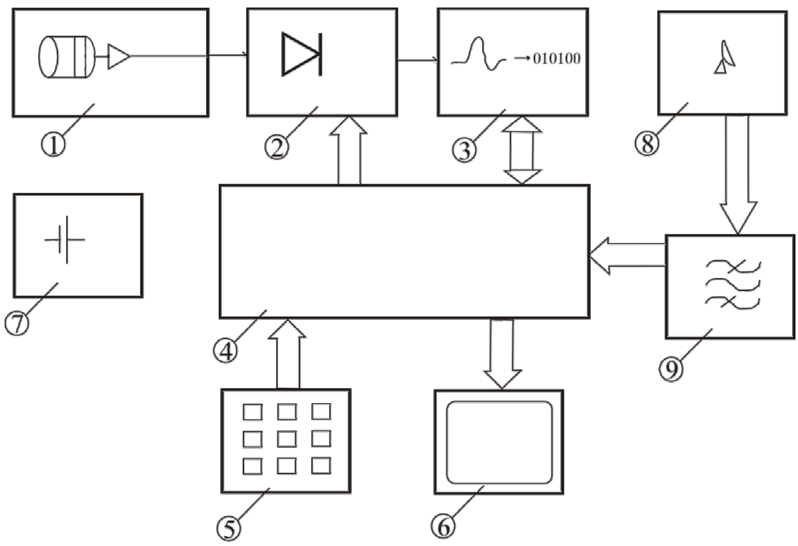

Figure 3.1. Block-diagram of "Gammamapper". 1 – gamma sensor, 2 – peak detector, 3 – analog to digital converter, 4 – micro controller, 5 – keyboard, 6 – LCD display, 7 – power unit, 8 – GPS engine, 9 – GPS data filter

and a rich set of on-chip peripherals [25].

Control code written by the author also handles storing measurement data to a standard compact flash or multimedia card.

Spectrometer uses a “one-wire” temperature sensor from Dallas [8] to compensate for possible drift of readings [29] due to ambient temperature changes. Sensor’s readings are stored together with spectral data to the same file.

Embedded microcontroller also keeps track of geographic coordinates obtained through a prefilter (9) from GPS engine (8). Status of instrument’s battery (7) is constantly monitored and displayed on main screen (6) in graphic form. In case of power failure measurements are terminated and all acquired data is saved to memory card.

In the next chapters of present thesis operation of instrument's various units will be described in greater detail.

4. Analog front end of Gammamapper

The purpose of analog front end circuit is interfacing gamma detector's output to intruments embedded processor's ADC input delivering unipolar signal stable during acquisition time. Different detectors use different signal levels. Common options are bipolar and unipolar signals (see figure 4.1).

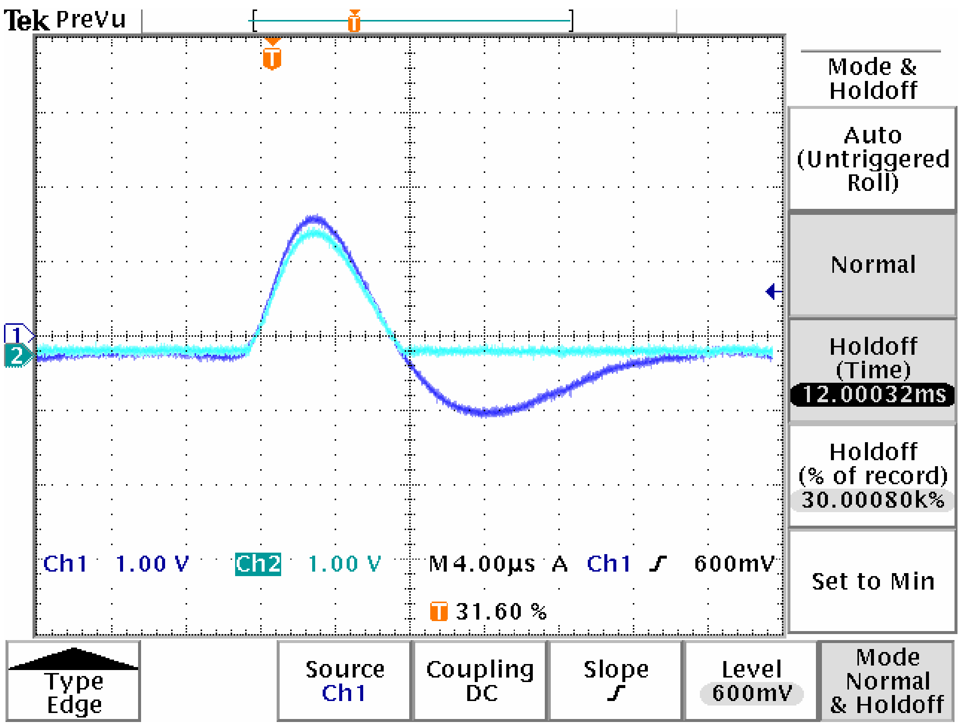

Figure 4.1. Bipolar (dark-blue) and unipolar (light-blue) impulses

Both versions have their main application areas. Bipolar signal is applicable in high count rate systems where signals baseline tends to drift due to incomplete discharging of coupling capacitors in spectroscopic amplifier and other parts of the system [30]. Signal with both negative and positive components discharges the mentioned capacitors and in some cases a separate BLR unit (like described in [4]) is not needed.

In slow count rate environmental instruments like the present spectrometer, base line (zero level) drift introduced by capacitors is negligible and may be left uncompensated. In order to reduce possibility of zero level distortion even more, the circuit has been designed without any additional coupling capacitors in signal path. One can assume that there are some in detector circuit. Unfortunately exact information about detectors construction was not available. Since detectors output pulse is bipolar, baseline drift will be compensated anyway.

Zero drift of spectrometer's signal path depends on several factors: ambient temperature, stability of power supply etc. In the present instrument the first attempt to eliminate drift was taken in circuit design. Front end uses separate stabilized dual power supply. Components were selected with minimal temperature drift.

4.1. Signal polarity converter.

Scionix's gamma detector V10P25/10-E3-Cs-T-X used in present spectrometer outputs a bipolar preshaped gaussian pulse with peaking time of 2 μs. Main processors internal ADC used to digitalize impulses, works with positive signal only. Therefore impulses are fed firstly to a detector built on a fast operation amplifier AD8034 (U1 on figure 4.2).

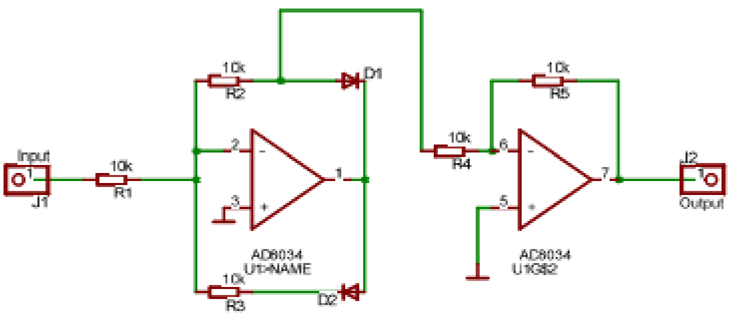

Figure 4.2. Signal conditioner converts bipolar impulses to unipolar for the ADC

According to manufacturers data [32] this amplifier has a voltage slew rate of 80 V/ μs and the device is stable even in unity gain connection. OPAMP also features low power consumption – 3,3 mA. Second half of dual OPAMP U1 is used as an inverting buffer with unity voltage gain. In the output of detector we have unipolar (positive) impulses ready to be converted to digital form. Conditioned signal measured at converters output is shown with a light-blue color waveform at figure 4.1

4.2. Peak detector

During sampling time of an AD converter, signal level on its input must be held constant. A peak detector on U2 (see figure 4.4) serves this purpose.

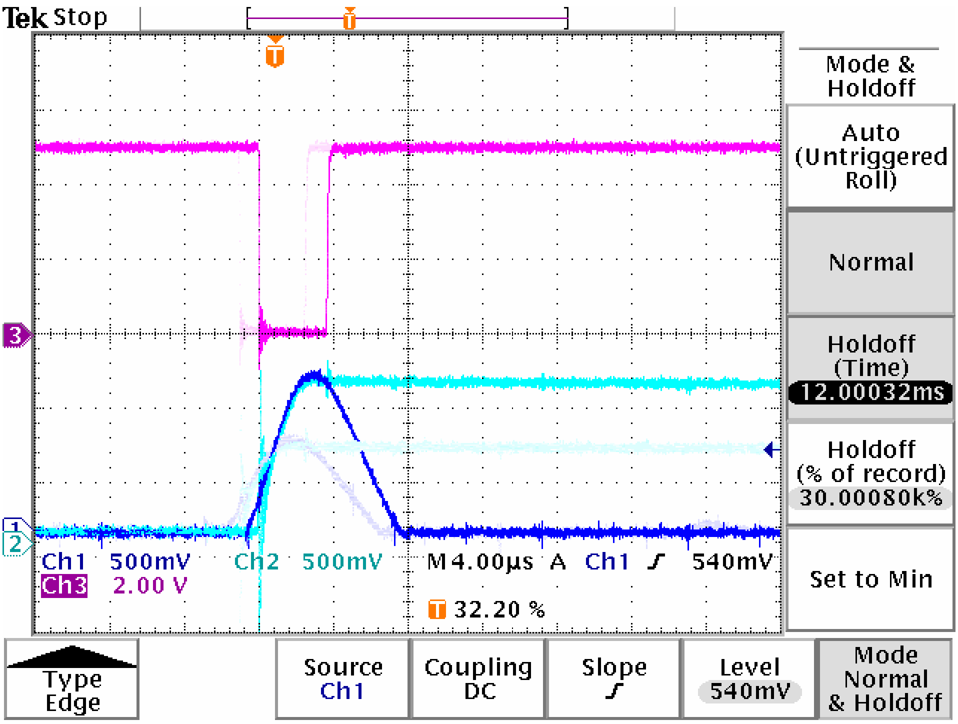

Figure 4.3. Input signal (dark blue) is captured by peak detector (light blue). Then a PDET conversion start signal (magenta) is generated. Rising edge of impulse starts the cycle.

Peak detector constantly samples gamma detectors output. For accurate digitalization of input signal ADC conversion must be started exactly on the moment detector's pulse has reached its maximum. In present circuit this is achieved with a fast comparator LM311 (U4). Comparator also acts as an interface element between analog and digital parts on spectrometer. Its output is on a high logical level during input signals positive front. Then voltage on comparators both inputs rises in nearly equal time. A small differential voltage introduced due to time constant of integrating circuit R13, C12 helps to keep comparators output „clean“ preventing false triggering.

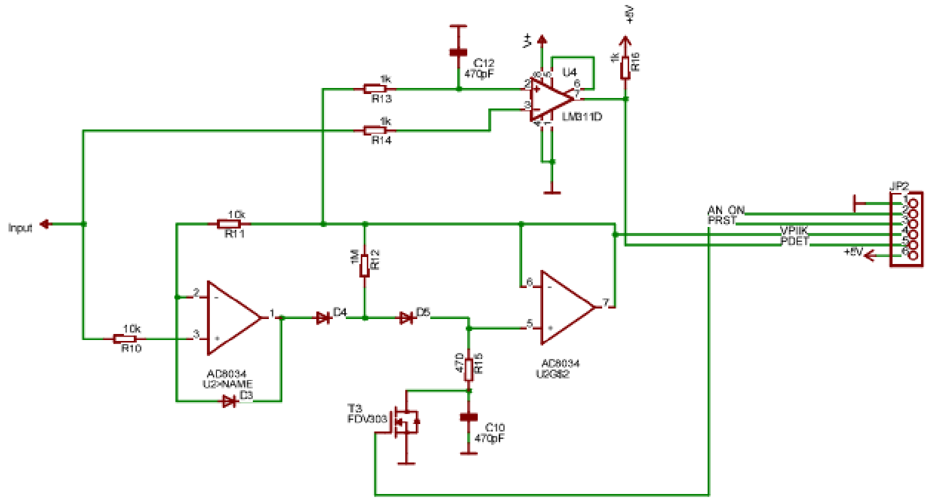

Figure 4.4. Peak detector's circuit

After peaking time pulse's amplitude starts fading and voltage on comparators inverting input falls. Voltage on positive input coming from peak detectors output remains constant. The comparator is triggered, it's output goes to a low logical level. This event is used to start main processor's ADC (signal PDET, see also figures 4.3 and 4.5).

ADC is built on switching capacitors technology. Internal holding capacitors are charged from input signal after conversion is started. Acquisition time must be long enough to allow complete charging. Therefore during acquisition signal on ADCs input must remain constant [2,18,19]. Instruments main processors ADC unit has an automatic acquisition mode. Conversion is not started right after corresponding triggering signal but a predefined delay is automatically introduced. Required minimal delay for a 20 MHz clock frequency is 2,45 us. This is set during microcontrollers initialization.

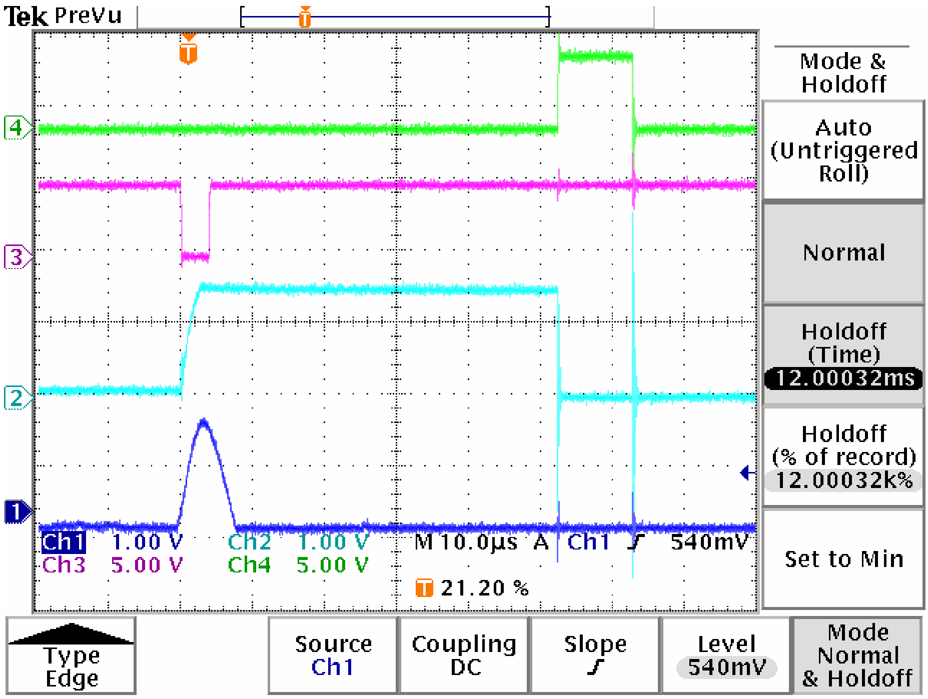

Figure 4.5. Signals controlling peak detector and detector's output

When conversion completes, a digitalized value is compared by microcontroller against a preset low level threshold and if it is greater then data is stored to processor's gamma data buffer. If not, the impulse is discarded. In both cases peak detector must be reset (sampling capacitor C10 discharged) before next gamma event could be recognized. Reset is initiated by a controller under software control; logic level controllable FET T3 acts as a low impedance reset switch.

Resistor R15 has a critical role in peak detectors stability during reset operation. Without this component negative feedback would be cut off causing circuit's spurious oscillations. Stability is better when component value is increased. During normal operation of detector too big resistance of R15 may introduce additional error in digitalization process. A trade-off value of 470 ohms was found experimentally.

As mentioned earlier, a stabilized and filtered dual power supply is essential for accurate operation of peak detector unit. +5V power is obtained from main supply via noise supressing LC-filter L3, C19 (see complete circuit on figure 4.7). Gamma detector unit has its own filter L5, C28.

Negative supply voltage -5V for OPAMPs is generated by Maxim's charge pump IC U7 connected in standard configuration. Device is capable of delivering current up to 20 mA. Spectrometers analog front end consumes about 11mA.

In order to reduce energy consumption, analog circuitry is activated only during acquiring spectra.

4.3. Low- and high level discriminators

Many MCA-s implement hardware low- and possibly also high level discriminators enabling filtering out impulses with unwanted energies. CsI(Ti) detectors sensititivity is energy dependent with a significant rise in region of low energies. In many cases theses impulses carry no information, they could be considered as noise. Unwanted pulses of low energy could be filtered out in hardware without any software overhead with a simple circuit shown on figure 4.6.

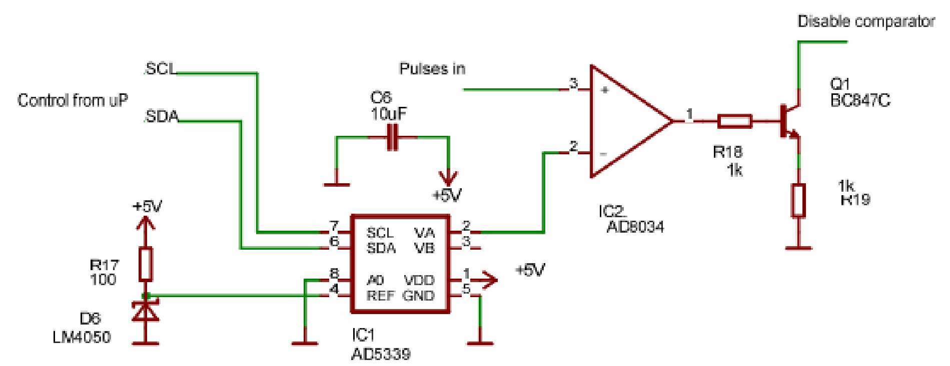

Figure 4.6. Low level filter circuit

Microcontroller sets lowest level for registered pulses with the aid of a DAC IC1. Comparator IC2 compares incoming pulse's amplitude with preset by microcontroller reference voltage and if it is lower, blocks conversion start signal via transistor Q1. Low threshold (calibrated in energy units) could be altered via spectrometers GUI. In instruments present realization level discriminators were transfered to software layer in order to reduce power consumption. This approach slowed processing of pulses only for 1,2 μs. Firmware sends commands to a hardware discriminator at measurement start anyway thus enabling a faster responce if needed and if appropriate hardware is present. Instruments circuit board has places for corresponding chips.

Analog front end of „Gammamapper" is realised as a separate unit. It could be replaced with a more advanced one or with a unit designed for different radiation sensors. Modular approach should make overall design of „Gammamapper" more flexible.

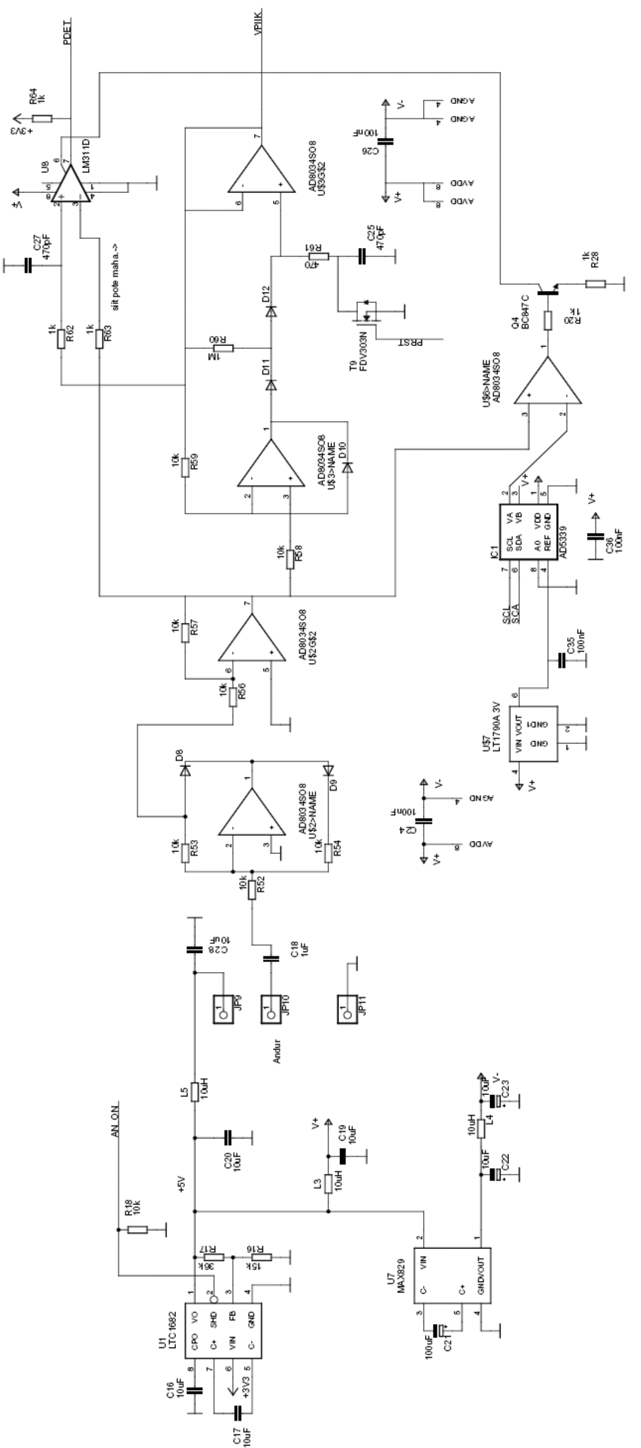

Figure 4.7. Complete analog front end circuit of the „Gammamapper“

5. Digital part of Gammamapper

The main task of Gammamapper's digital circuitry is controlling all other units of the instrument and acting as an interface to user. The unit controls analog front end setting up correct sequence for peak detector, communicates with GPS prefilter and retrieves geographic data from it if available. Processor generates all commands needed to initialize and exchange data with a color LCD display [44]. PWM-signal for screen's backlight is also generated by the controller. Processor controls a SD-memory card, maintains its file structure and stores measurement results to it. Presently only a standard FAT16 file system is supported.

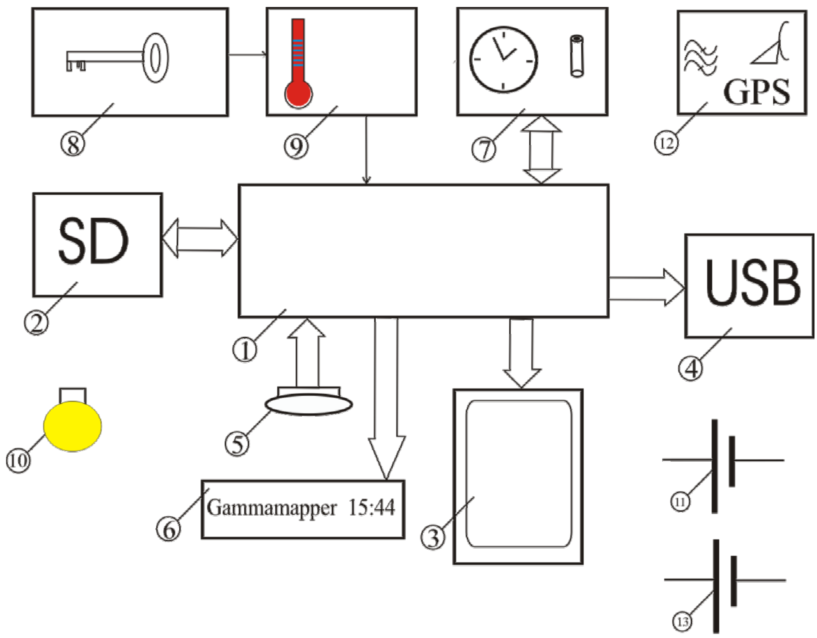

Figure 5.1. Block-circuit of digital part of Gammamapper

1 – microprocessor, 2 – memory card for storing measurements results, 3 – color LCD display, 4 – USB communication interface, 5 – multi-purpose navigation button, 6 – low-power auxiliary LCD display, 7 – real-time clock with back-up battery, 8 – crypto-key, 9 – digital thermometer, 10 – LED torch, 11 – supply for analog front end, 12 – GPS engine and prefilter, 13 – main power supply unit with battery charger

Since main processor (1, figure 5.1) of the spectrometer is the „heart“ of the whole instrument and its resources have a deep impact on the capabilities of the unit, it must be choosen carefully. The controller has to be fast enough to start measurement cycle after receiving a „PDET“ signal from front end circuit, measure peak-detector's output, store data and restart detector for next particle to be detected.

On the other hand acquiring spectra from low-activity sources as it is common in envionmental research can take a considerably long time (several hours). In case of powering the instrument from mains it would not be an issue but in an autonomous environmental research device low power consumption is necessary. For field measurements „Gammamapper“ is equipped with a 1,8 A/h capacity Li-Ion cell. Naturally the instrument (and its microprocessor) must implement a low-power design to enable long-lasting measurements. And at last the controller chip must possess enough I/O-pins for connecting to peripheral units like navigation button (keyboard analog), display, memory card etc.

Author chose a standard off-shelf micro controller PIC18F4550 manufactured by Microchip. This microprocessor has been designed in nanowatt technology consuming only 40 mA at maximum clock frequency of 40 MHz [25,26]. In „Gammamapper“ the processor runs at a 20 MHz clock crystal. Internal PLL produces faster clock signals for USB [43] interface.

Device features also rich set of on-chip peripherals which simplifies spectrometer's circuit design and reduces power consumption. Many tasks requiring usually extensive hardware like generating PWM-signal, measuring analog signal with an ADC, USB interface, etc are implemented in the controller chip itself making design faster and simpler.

Controller's relatively large on-chip RAM-memory (3,7kB) increases units responce to detected particles . Measurement's results could be stored to on-chip memory buffer with a much faster access time than a SD-memory card. Data is tranferred from buffer to a SD memory card after every 240 cycles when buffer is full. This process inserts an additional delay slowing instrument's responce. Among other parameters delay time depends of data clusters position on memory card due to the nature of disc access algorithm. Storing data to clusters addressed by the first sector of FAT takes about 14 ms.

Every 512-byte data sector saved consists of a 32-byte „header“ containing geographical coordinates (2*8 bytes), time (6 bytes), gamma sensor's temperature (2 bytes), battery voltage (2 bytes) and live time (4 bytes) (see table 5.1). Remaining 480 bytes are reserved for measurement results. The ADC present in main processor has 10-bit resolution, so results of 240 cycles can be stored in one data sector after which the sector buffer must be saved to disc. Such 512-byte data structure is dictated by the memory card architecture.

Table 5.1. „Header“ data structure in every data sector

Bytes	Contents	Note
1..8	Coordinates – N	ASCII text
9..16	Coordinates – E	ASCII text
17..23	GPS time	ASCII text
24,25	Temperature, sign, marker and shutdown bits	Binary, marker=sign.7, shutdown=sign.6
26,27	Battery voltage	Binary, big endian format
28..32	Live time counter	Binary, big endian

The first sector of results file may contain information input by user. This could be an experiment setup description, name of measurement place etc. A software timer with 10 ms resolution keeps track of measurement live time.

The first version of Gammamapper used a +5V supply. This was mainly dictated by parameters of Scionix's gamma sensor. Suitable 5V tolerant memory for spectral data was a CF-card. Later author decided to use a micro SD card (also known as a Transflash) in order to save board space and increase memory capacity. Electrically this change lead to use of simple resistive level shifting networks (see figure 5.2) since a SD-card's I/O is not 5V tolerant. A separate low drop-out linear stabilizer for powering the card had to be implemented also. The next version that is already being tested uses a single 3,3V supply for all devices on board of the instrument except gamma detector, +5V power rail for it is generated with a step-up converter.

Unlike many industrial designs „Gammamapper“ uses a graphical 132*176 pixel color LCD for displaying measurement results and interfacing to user. Display implements a built-in controller reducing main processor's tasks significantly.

Parameters of the instrument and measurements can be set via simple menu. Screen design (buttons, etc) was inspired by Apple's I-phone's approach. Unfortunately author did not have a touch screen. A status-line shows current parameters like time, temperature, GPS fix etc . During experiment a count per second value, current geographic coordinates and results file name are displayed on main workscreen. Version of firmware presently being tested also shows current live spectra as „seen“ by the instrument. Since this feature increases significantly the processors load and also responce time, it could be disabled from menu.

LCD display LS020B8UD06 used in the described circuit is not 5V tolerant. Simple resistive level shifters interface it to main processor. Display's LED backlight panel requires a driving voltage of about 11V at current 10 mA [44]. This voltage is generated by transistor T1 and inductor L1 (see figure 5.2). Diode D1 is rectifier. Filtering capacitors are built into the display. PWM drive signal is obtained from processor's PWM unit. This approach enables changing backlight intensity conveniently under software control. After successful start-up processor's PWM is configured to generate a 62 kHz and 50% duty cycle signal to feed backlight LEDs.

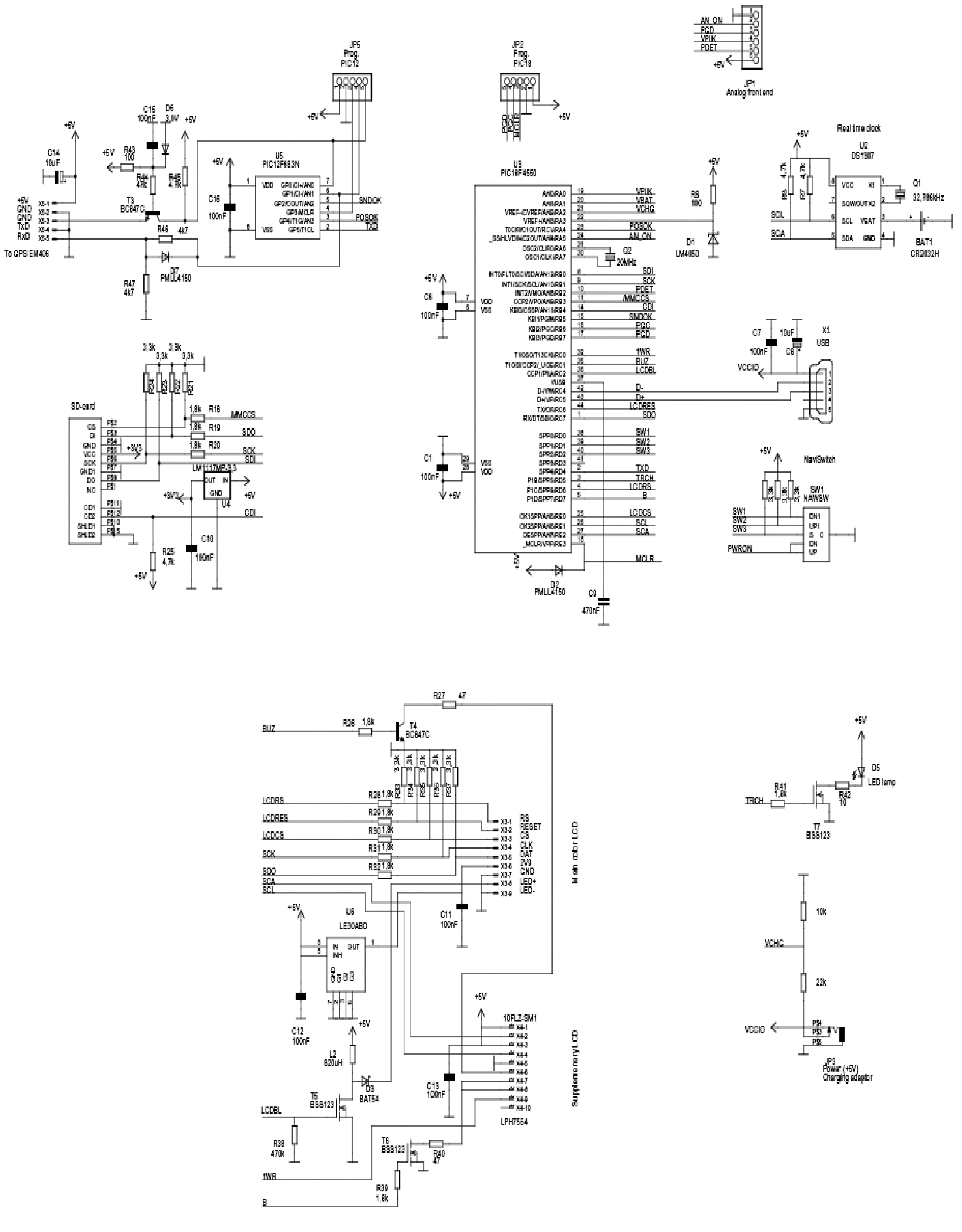

Figure 5.2. Schematic of „Gammamapper's" digital part

As mentioned above, every effort must be done to reduce instrument's power consumption in order to prolong battery life. Color LCD's backlight is one place for conserving power. Display is lit only during menu access by user. 10 seconds after last input a software timer shuts off backlight. Counts of particles detected and other more important information could still be viewed on a low-power auxiliary display (6, figure 5.1). This device consumes less than 1mA and is controlled via an I2C bus common to other units in the instrument as well. Backlight for both displays is restored for another 10 seconds by pressing the navigation key. Lights are constantly on when the device is powered from the USB connector.

A real-time clock chip (7, figure 5.1) from Dallas is built into the instrument.Time information from it is used if GPS fix is not available or measurements are started without using the GPS-engine. File creation time is also obtained from the RTC chip. Clock supports daylight saving mode, correction is done in software and could be disabled. Clock could be synchronized by correct time information from the GPS engine. Validity of RTC info is determined by a control byte written into it's RAM memory area. If chip's back-up battery fails, control byte will be corrupted also.

Electrically the RTC unit [1] consists of the clock chip, a dedicated crystal resonating on a 32,768 kHz frequency and a 3V back-up battery (see figure 5.2).

Literature sources [29] suggest possibility of peak energy shifts due to ambient temperature changes. Spectrometer uses a digital temperature sensor from Dallas in thermal contact with the detector. Sensors readings are stored with spectral data to the same file. This approach should enable recalculating and correcting once measured spectral data later in case a better correction algorithm is found. Addressable sensor chip DS1820 features low power consumption and 9 bits resolution [8]. Control and data exchange is done via 1-wire bus. Several similar thermometer chips can be connected to the same 1-wire bus if needed.

5.1. GPS engine and prefilter

In many areas of science (as in material science or enviromental research) it is essential to have the measurement data bound to spatial coordinates. For example let us consider moisture contents measurements. Walls of buildings are not even, repeatability of measurements can not be guaranteed by ordinary means. Cases exist where even 3 coordinates are not enough to guarantee needed accuracy and repeatability of measurements. A good example is measuring moisture contents of various materials. Since the 30 cm range moisture sensor of „Moist 200“ instrument uses polarized microwave radiation, it is essential to determine the probe's spatial orientation. If the tested sample/object has a fibrous structure, results depend much of sensor's rotation angle around its longitudinal axes. The described effect is clearly visible when measuring, for example, moisture of paper. For such cases a more precise 6-DOF positioning system as described in [Article IV] could be used.

Described above a 6_DOF system was tested on Gammamapper. It was estabilished that resolution of GPS receiver only was satisfactory for most cases.

Author uses an EM406-type GPS receiver in present gamma spectrometer's prototype. Combining geographic coordinates and energy of gamma particles detected allows building a radiation map. Also the nature of the process how ordinary man collects radiation doze can be studied.

Modern GPS engines have lots of attractive features: they are small and economic, output data could be read easily. Due to minute power consumption use of such a receiver in battery powered apparatus is justified. Data from a standard GPS-receiver is output in form of various so-called NMEA sentences. In NMEA mode data is presented as a stream of ASCII characters [23,37]. A „SIRF-Star" binary format also exists.

The receiver's output stream combines lot of information divided into different protocols. Device description is usually also transmitted on engine power-up. On start-up or in poor visibility the acquired coordinates might not be valid. For example in protocol $GPRMC (Recommended minimum specific GPS/Transit data) used in „Gammamapper", a special character – letter 'V' or 'A' indicates fitness of data.

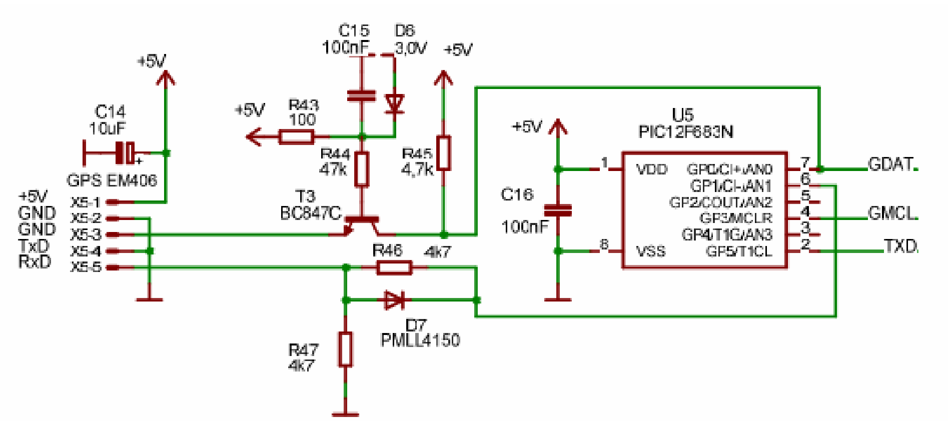

Figure 5.3. Circuit of GPS prefilter

In „Gammamapper's" prefilter author used Microchip's low-power microcontroller PIC12F683. This processor is a low-cost, economical device equipped with lots of peripherials and built using company's NanoWatt technology. Author described the first „release"of geodata prefilter in [Article I]. In a nutshell the prefilter consists of a microcontroller and level shifters (see figure 5.3) since used in the instrument GPS engine EM-406 output port is not 5V tolerant.

Processor U5 receives data from GPS engine via level shifting circuit based on transistor T3. Zener D6 biases transistor's base. Possible uplink to engine uses more simple level converter at R46, R47 and D7. In present version of prefilter firmware mentioned uplink is not implemented. In future versions it could be implemented for issuing configuration commands to the GPS engine.

5.2. Data encryption block

One important feature offered by spectrometer's main processor is protecting measurement results. This could be done by ciphering data.

A widely used memory chip called an I-button and containing a unique 48-bit unalterable number is used as a crypto-key. According to manufacturers datasheet this device can operate on “phantom power” derived from data line.This property is valued in a low-power design. Another attractive feature is that many devices using the same Dallas' defined command set and bus protocol could be connected to the same line. Since pin count of “Gammamappers” main processor was limited, author connected temperature sensor and I-button on the same data line.

The crypto key is needed only in case encrypting of data is enabled. Key is inserted only once after starting measurements minimizing thus power consumption even more. “Gammamapper” allows transferring of encrypted files to a host device or deleting them only after inserting the key again.

No other instrument presently in the market offers ciphering of results.

5.3. Power supply unit

Power unit of Gammamapper must fit within relatively tight limits. It must have a small footprint and be highly effective to ensure long battery life. Additionally a wide input voltage range is required since voltage on battery terminals alters from about 2,8V to 4,2V in case of Li-Ion cell. Charging of NiMh chemistry batteries used in previous version of Gammamapper produced even 5,5V at battery pack. Only a buck-boost converter can acommodate with such input voltage range. A suitable converter chip was present in Texas Instruments product folio: TPS63000 [31]. The device has efficiency of about 96% and it allows input voltage sweep in range of 1,8V..5,5V. For reliable startup battery voltage must be at least 1,9V. The device has many useful features like soft start-up reducing current inrush peak at start allowing thus boot-up from deeply discharged batteries. Soft start is accomplished by circuit R1,C2 (see figure 5.4). Converter is enabled by pulling its ENABLE pin (6) low by instruments multifunctional switch SW1.

Li-Ion batteries used in the instruments present version, need protection against deep discharge. According to [22] minimum voltage on one cell can be as low as 3,0V. Absolute minimum is 2,7V: discharging below that level causes irreversible changes in battery's chemistry.

On power-up microcontroller measures battery. If its voltage is found to be higher than mentioned minimum level, processor holds the converter in active state via transistors T1,T2 (see fig. 5.4). Battery status is monitored constantly and displayed in graphical form. If the battery is discharged below 2,8V, measurement activity is terminated, all opened files closed and the device is switched off. A special mark is written in datafiles header indicating that measurements were terminated prematurely due to the end of battery life.

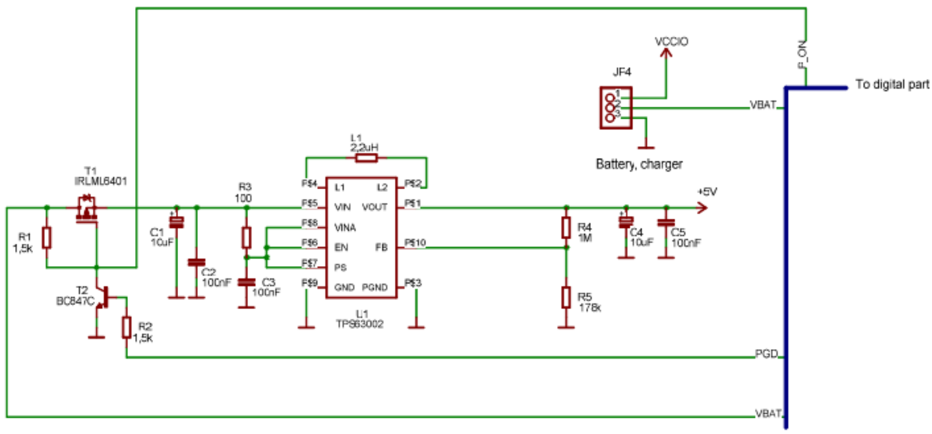

Figure 5.4. „Gammamapper's“ power supply circuit

Converters output +5V rail feeds all internal electronic units of the instrument. Main loads are the microcontroller consuming about 10 mA at a 24 MHz clock fequency, instruments LCD display backlight (10 mA) that is active only during short periods, GPS engine (consuming about 60 mA) and analog front end board.

Present version of „Gammamapper“ is capable of at least 7 hours of continuous measurements.

Analog front end (see fig. 4.7) of „Gammamapper“ requires its own stabilized and filtered +/-5V supply. To reduce power consumption this unit is activated via path An_ON only during measurements. -5V supply for OPAMPs is generated by a charge-pump topology converter built around a MAX829 chip. Additional LC-networks ensure filtered „clean“ supply.

A 4,096V reference voltage for processors ADC is aquired from a precision reference source LM4250 (see fig. 4.9).

5.4. Miscellaneous options

A LED torch is built into described spectrometer. Although this device will not enchance the instruments performance, it adds convenience in usage. The ultrabright LED (10 on figure 4.8) features high brightness consuming only 10 mA. The torch can be swithed on and off via menu button both during measurements and the device idle state.

A buzzer device is used to signal various events in the devices operation (GPS lock achieved, errors etc). Buzzer could be programmed for audible alarms signalling that energy of detected particles falls into range of interest. Buzzer can be set to signal accumulation of preset number of counts also. Net R1, C1 filters out glitches in power rail generated by the buzzer.

Instruments battery is charged by a dedicated power management IC U1 (MCP73833, see figure 5.5) manufactured by Microchip [42]. The device acquires input power +5V from a standard USB connector. Red LED (LED1 at figure 5.5) indicates charge in progress and green - LED3 signals end of charge. Complete charging of instruments battery takes about 180 minutes.

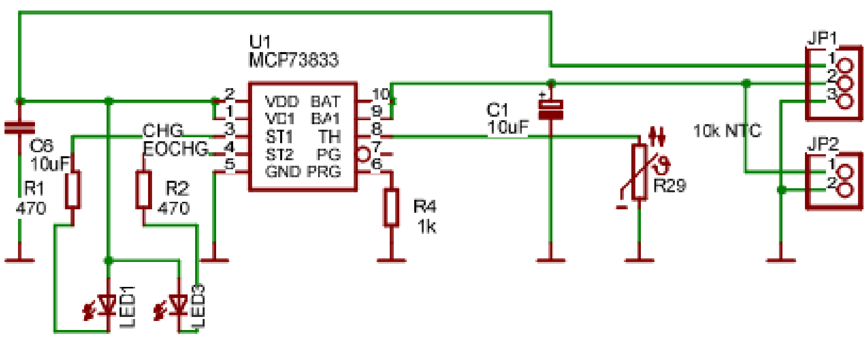

Figure 5.5. Gammamapper's battery charger unit

6. Software for Gammamapper: firmware and PC utility

The majority of firmware for modern instruments is written in some high-level programming language. C is perhaps most common of them. Lately instruments running an operating system (cell phones) have become common.While high level programming languages shorten significantly development time, they also need more processing resources like code- and data memory. In some cases writing firmware in assembly language is more beneficial since it produces very compact and high-speed code. Also programmer has exact control over devices resources.

Since control of Gammamapper's front end and later data processing is implemented in software, it needs to operate at high speed in order to improve instruments throughput. The firmware for „Gammamapper“ is written entirely in assmbly language and compiled with tools of Microchip's free development environment „MPLAB“. Resulting code file's length is about 70 kB. Source code is too capacious (about 327 kB of text) to be fully analyzed in this work . Therefore only more important parts of it will be described in this chapter.

Tasks of the instruments main processor can be divided into two major categories: system maintaining processes such as testing hardware at start-up, processing user input and communicating with peripheral devices. Second category of processes include actual measurement.

It must be possible to change some instrument's parameters (like alarm buzzer's sensititivity) during measurements. Battery power must be monitored and device's display updated constantly. In some particular location (e.g. where count of pulses rises significantly or an unexplained object is found) the experimenter may want to flag place's coordinates. In order to inspect some object in darkness built-in torch must be used. This means that the navigation button should be queried during measurements as well.

In order to realize this kind of pseudo-multitasking, the device is set to run system tasks constantly in main flow loop. Measurement processes are run in background using processors sophisticated interrupt system. Such approach makes processing detected particles and other important tasks transparent to the operator. Assembly language code provides speed and necessary computing power.

6.1. Starting measurement cycle and storing analog values from peak detector

The work cycle of Gammamapper is started from the main menu selecting the upmost key. A sub-menu offering various options is then displayed. Then user can choose to add a short note describing experiment (up to 512 characters), GPS engine could be switched off for measurements conducted in a fixed location. The last option is autostart. This and the use of GPS is remembered and applied to next measurements as well without the need to select it from menu. This feature makes the starting of the experiment easy – user only has to press the navi key for powering on and starting work with previous settings.

After all selections are made instruments processor applies power to analog circuitry and introduces a 20 second delay. The delay is needed for stabilizing Scionix's gamma detectors internal bias converter [29]. Right after powering up signal from the detector contains much noise.

At the same time microcontroller starts looking for a GPS position fix (if GPS is enabled) monitoring state of prefilter controller's Pos_OK pin. If GPS fix is achieved and power-up time has ended, the main processor resets peak detector, initializes data memory pointers, opens file on SD-disk and enables vectoring to interrupt Ext_Int0 which is generated every time a particle is detected.

Mass storage media is organized as units of 512 bytes. Data can be written or read only 512 bytes (one block) at a time. Using a 10-bit resolution ADC, every measurement occupies 2 bytes. Additional header of 32 bytes containing geographical coordinates, GPS time, detector temeperature, battery voltage and measurements live time is inserted at the beginning of each block (see table 4.1). A memory buffer for described data and results of 240 measurements is set up. As soon as required amount of measurements is completed, live timer is stopped, interrupts are disabled and contents of data buffer is transferred to SD disk. As a result we have a file containing „raw“ data i.e. all gamma events the instrument has detected. This solution lets researchers reanalyze data in case more sophisticated processing algorithms are developed.

Constantly updated FAT table of disk is kept in instruments RAM and stored to disk only when experiment ends or battery is exhausted. Using controllers RAM instead of updating necessary data on the disk serves two purposes. Firstly this increases data processing speed (a sector write to disk takes about 15 ms). Secondly every flash memory (SD-disk is also a flash memory) has limited number of write cycles. Most commercially available flash products are guaranteed to withstand around 100,000 write-erase-cycles, before the wear begins to deteriorate the integrity of the storage. Updating FAT info only after file is closed helps to increase disks life time.

6.2. Displaying acquired spectra on the fly

Nearly all professional gamma instruments use a separate computer where acquired spectra can be viewed and analyzed. Sometimes it would be desirable to have some simple means for viewing acquired data on the fly without additional equipment. Gammamapper can display measurement spectra

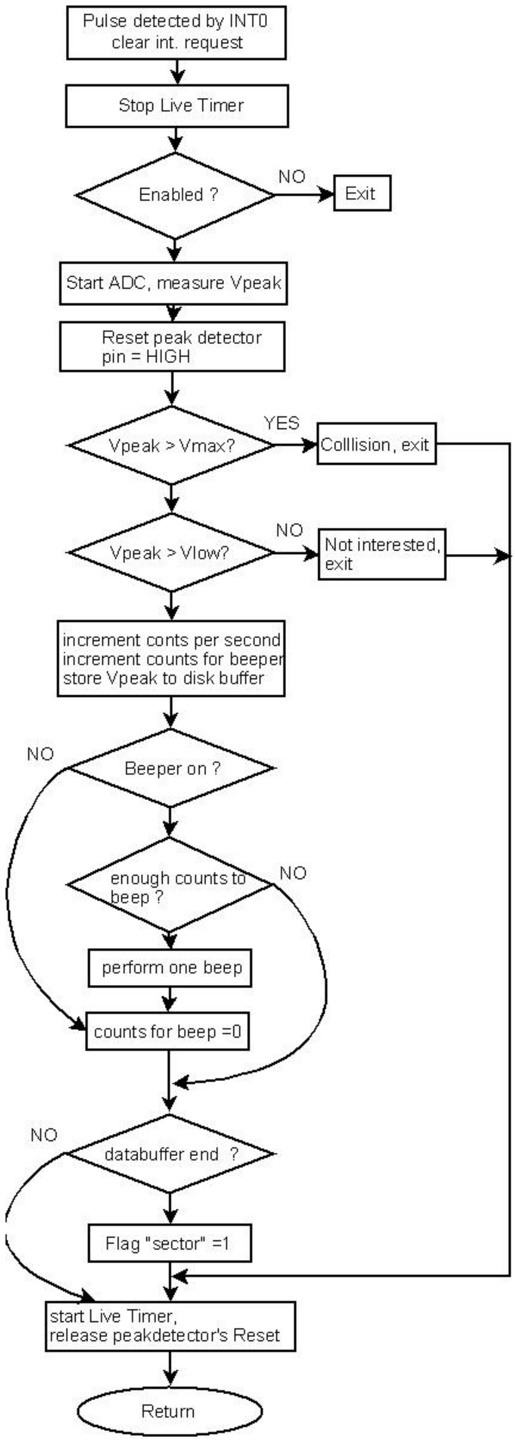

Figure 6.1. Processing of input signal pulses

on its internal color LCD dislay during measurements. Every time a measurement buffer must be saved to disk, its content is converted to a spectra, normalized and displayed. Logarithmic and linear intensity (Y-) axis can be selected for display. The flowchart of the measurement processes algorithm is displayed on figure 6.1.

The device uses a 132*176 pixel color LCD. Spectra contains of 1024 channels (X-axis) dictated by processor's on-board ADC's resolution and is displayed in a 128*128 pixel window. Therefore a conversion is needed to fit spectra on display. Every channel has a 3-byte counter containing a maximum of $2^{24} = 16777216$ counts. This means that a normalization algorithm is needed for this axis as well. A channel with maximum number is found. Knowing that display areas max_Y is 128, a normalization coefficient is computed and contents of every channel is divided by that factor.

For X-axis normalization spectra is divided into groups of 8 channels. The maximum value of each group is calculated and this value is used in display routine. The described algorithm is reused in devices normal spectra viewing mode when measurement is not active. Spectra displaying algorithm is presently being designed and tested.

6.3. GPS prefilter

As mentioned earlier in the present work, it is highly desirable to have an automated and accurate means of acquiring qeographic coordinates of measurement place. In a mobile device like the present „Gammamapper“ or other "GPS-aware" embedded instruments traditional solutions like using compass and other „manual“ navigation instruments would be extremely impractical. This is especially true in case continuous measurements are needed to be carried out from a moving vehicle.

One solution to this problem is using a GPS receiver. Modern GPS engines are compact and low-power devices making their use in portable instruments justified. Engines output data could be read easily since most of them use a standard NMEA protocol [23].

Problems arise when instrument equipped with a GPS engine must acquire large amounts of data that arrives in a random manner. This is exactly what happens in a gamma spectrometer since ionized radiation is random by nature.

A trade-off must be found to ensure that every particle captured by the detector is digitalized and stored. On the other hand the GPS output stream is relatively slow. Common engines usually default to a 4800 bps transfer speed. It is possible to use main processors interrupts to automatically vector to analyzing GPS stream and then return to processing a possible gamma event but certain problems still persist. Engine outputs not only needed data (coordinates and time) but also several other so-called protocols containing data about magnetic variations, land speed, available satellites etc. Instruments own processor would have a lot of work filtering useful data from raw stream.

On some models unwanted protocols could be switched off but an eye must still be kept on validity of data (i.e. in case user moves into a location where radio reception is not good). On start-up or in poor visibility the acquired coordinates might not be valid. For example in protocol $GPRMC a special character – letter 'V' or 'A' indicates fitness of data. More information about protocols used in GPS data transactions and their meanings could be found from [21,23].

Spectrometes main processor must take this sign in consideration and replace geodata with the last valid one. This would increase even more instruments processing overhead and could even lead to skipping valuable gamma events. Authors experiments with gammamappers first prototype indicated that this was exactly the case.

One possible solution to enlisted problems would be using a separate low-power microcontroller dedicated only to analyzing GPS engines data stream and filtering out needed information. The device should also buffer data for some predefined time in case of poor reception conditions.

Prefilter's processor constantly monitors GPS-engine's datastream looking for protocol starting with sequence: „$GPRMC“ (Recommended minimum specific GPS/Transit data). Should some other protocol be needed, one simply has to change it's name in the end of the code block in table „*VastusGPRMC*“). Sample protocol looks like the following:

$GPRMC,081836,A,3751.65,S,14507.36,E,000.0,360.0,130998,011.3,E*62

After mentioned above start combination is found, the code starts analyzing incoming data and stores predefined fields into memory.
Firstly it looks for a character in field 3 – the navigation receiver warning. 'V' means that coordinates are not yet determined. All data will be ignored and the code returns to protocol search cycle. If the mentioned character is 'A', data is considered valid and algorithm will continue selecting coordinate and time info which will be stored into memory. Other symbols will not be stored.

Protocol „$GPRMC“ ends with an asterisk '*' symbol followed by checksum.

First firmware described in [Article I] used relatively slow and simple datalink to main processor. Data buffering was not very good. In present version (2.1) prefilter sends data on main processors request in 28 us. The code is designed to allow other interrupts being enabled during GPS communications. Double buffering is used. If both coordinate buffers are empty, or data is considered „old“ (after 4 seconds since last request), chip signals it to the instrument. This will happen when satellites are blocked from engine's view (e.g. moving to indoors).

Code for the prefilter is written in assembly language to ensure high-speed operation and compact code file (device's code memory is limited).

Good practice suggests thorough testing of firmware against real life situations to reveal all possible bugs. Since GPS signals were not available in lab, some kind of test generator is needed. This test device should also be able to simulate errors in transmission that are always present in real cases. An attempt to design such test device is described in more detail in [Article VI]. It proved to be extremely useful for the author in debugging GPS-prefilters firmware. The test device consists mainly of a microcontroller. Two switches for changing working modes are also included. Later work added several new and useful features to the tester. Most important of them is the possibility of defining users own protocol making use of the test sequence generator in other applications as well.

6.4. Data encryption unit

Although data, especially scientific one should be freely accessible to everybody interested, it is sometimes desirable to protect experiment results. Protection may include disabling accidental erasure of files like in the described instrument and, sometimes, even restricting access to files in question.

Traditionally protection is carried out in computers, where experiment data is stored. Cryptoalgorithms are complicated but fast and reliable.

In author's prototype gamma spectrometer operator can choose to crypt data (from measurements menu) before starting an experiment . Instrument then marks the file. Without posessing the key, other operators cannot use measurement results. Perhaps more important is the fact that they can not (accidentally) destroy datafile.

There are many ways to generate a crypto key. One could use keypad to input the key, read it from some kind of external memory etc. The author used a standard and widely spread memory key producing a 64-bit unique number. Manufacturer – Dallas – calls it an I-button. This means of inputting crypto key is:

1. convenient – user does not have to remember or write down any numbers;
2. quick – I-button can communicate with speed up to 16 kBits/s;
3. cheap – I-button is widely used in various electronic (phono-)locks resulting in low cost and availability of the key-chip;
4. power consumption is reduced to minimum: the button derives power from data-line and only during reading. In a battery powered instrument it could be an issue.

Scientific instruments can produce results at high speed. This is also the case in the author's prototype. Therefore a crypting algorithm should be compact and fast. One possible solution is Vernam cipher [27]. Some authors even claim, it is the only currently known unconditionally secure cipher, provided the key is truly random .

Vernam cipher is a stream cipher in which the plaintext (measurement data) is XORed with a random or pseudorandom stream of data (the key) of the same length to generate the ciphertext. The algorithm is fast and not very demanding on hardware (see figure 6.2).

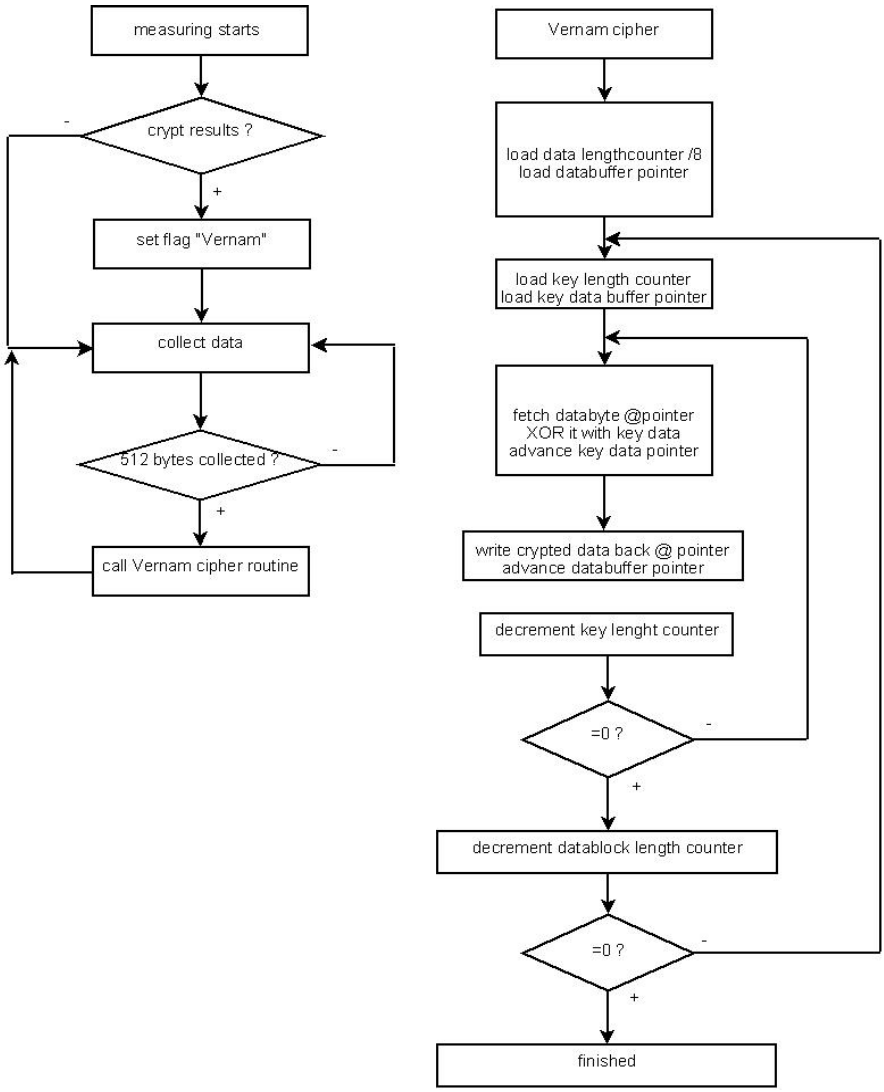

Figure 6.2. Flow diagram of data encryption algorithm

In author´s prototype instrument data is saved on a SD-disk with sector length of 512 bytes. Every time spectrometer's processor has collected as much results, a Vernam-cipher subroutine is called (if operator has enabled this option) and the result is then written to disk. This approach permits carrying out measurements at full speed introducing an additional small delay due to ciphering only during disk write operations.

File system of the spectrometer demands inserting a key (I-button) also in case an attempt is made to delete crypted file. This should minimize the risk of accidentally erasing valuable data files.

Deciphering of encrypted data is straightforward: one only needs a key and its reader. For I-button the reader consists of two contacts only. There is no need for a special decoding program - same encryption function works as a decrypter due to the symmetrical nature of the algorithm.

There are many methods of breaking code. Since data in described instrument is in binary form, it should be not so easy to crack the cipher because it is hard to tell if the result of hacking makes sense or not. Things are much different with data in ASCII format.

It must be noted that crypted files on disk can still be erased on some other device (ordinary PC). But then again...the disk itself can also be easily destroyed if needed.

6.5. PC programm

To support designed system author wrote a small utility for visualization and data analysis. Figure 6.3 shows utility's working screens. Program uses Windows platform and allows plotting measured data onto geographical maps. To save computer memory only needed map quadrants are loaded. As the heart of utility's map engine, a free GIS environment – Map Window GIS is applied.

Transfer of files to a „big“ computer is needed not only for archiving purposes but for better analysis. Gammamappers main processor running at a 20 MHz clock and limited amount of memory is not capable competing with sophisticated analysis programs like Genie 2000 or even MS Excel. Those programs have been developed by large teams of specialists spending probably hundreds of hours for developing code. It seemed to be unreasonable to compete with them.

On map user can select regions for which gammaspectra will be plotted. For better visualization on map, waypoints can be colored according to the energy of gamma particles detected in these points. Defining of Regions of Interest is done via spectra tools screen.

The spectra viewing tool of the program allows adding or subtracting spectra (i.e. subtracting background) and format conversions for exporting data. It is helpful if more powerful analysis programs are used.

During measurements experimenter can place a special mark (flag) to underline the importance of some location. Present viewer displays a special quadrate-shaped mark pointing at emphasized by the operator location's coordinates.

Possible notes describing viewed file and entered by the operator are displayed in a separate small text area. File creation date and time together with live time are also displayed.

Amongst other tasks program allows deciphering files encrypted by the instrument.

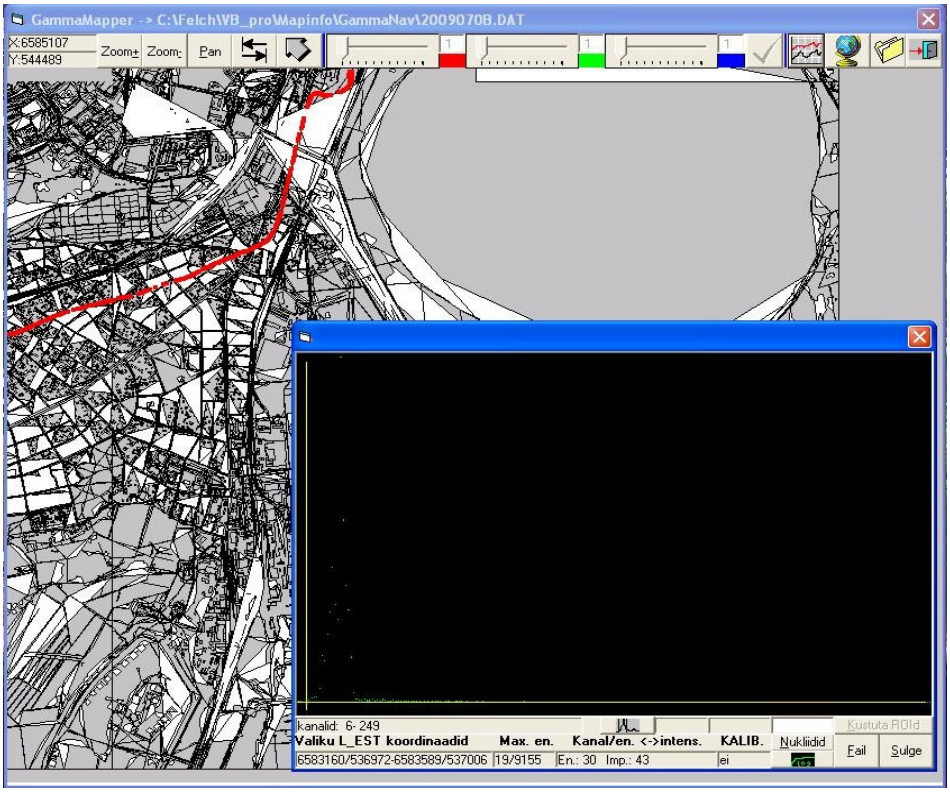

Figure 6.3. Main screen of results viewing utility

7. Measurements with Gammamapper

A prototype of portable autonomous spectrometer for gamma radiation was designed, built and tested during present work. Photo of the device is shown on figure 7.1.

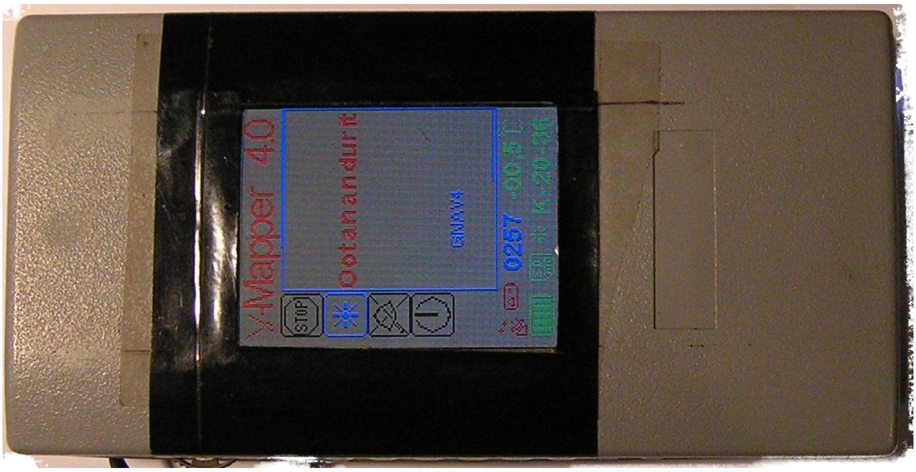

Figure 7.1. Prototype of a portable gamma spectrometer „Gammamapper“

One important parameter of a (gamma -) spectrometer is its resolution (without detector because detectors resolution is a known parameter) and linearity of its analog circuitry. In this paragraph we try to determine the mentioned parameters. Author used versions of Gammamapper in real field measurements during 2 years. Results of those measurements and some acquired spectra are also discussed.

7.1. Measuring Gammamapper's main parameters

In order to measure resolution of instrument's analog front end a test signal in form of Gaussian pulses was fed to the instrument. Duration of pulses was 40µs, frequency 6 kHz and amplitude 0,5V to 2,0V. A gaussian pulse was selected to immitate gamma detector used in present spectrometer.

In ideal case all measured pulses should fall into one channel giving only one sharp pulse at the „spectra“. In real cases the peaks width occupies more than one channel. Its maximum falls into one channel, fading pulses could be observed in previous and trailing channels as well. A histogram describing distribution of pulses in neighbouring channels is shown on figure 7.2.

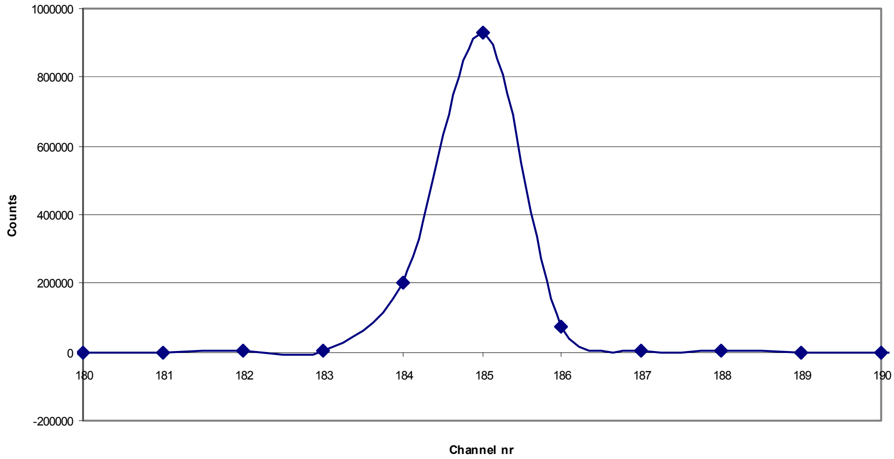

Figure 7.2. Scattering of pulses into neighbouring channels with a 0,5 V gaussian input signal

A pulse is spread to about 3 channels. Scattering may be caused by parameters of analog front end and also by the unstability of test generator used.

Results show that a resolution of about 0,6% is achieved. According to literature sources [14] this can be considered to be a good result.

In order to determine analog parts linearity the abovementioned signal was applied to input. Pulses amplitude was increased with a step of 0,5V and a „spectra" was acquired at each step. A graph showing the relation between channel number of the spectrometer versus amplitude of input signal can be constructed (see figure 7.3).

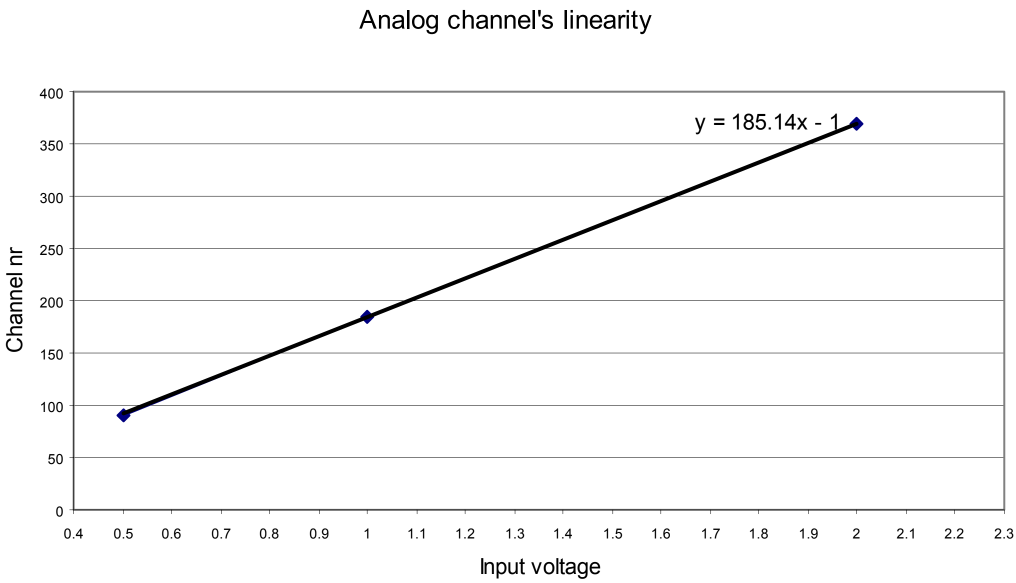

Figure 7.3. Input voltage versus channel number

Ideally this graph should be a straight line but in reality slight deviations characterized by device´s unlinearity factor are always present. Industrial instruments discussed in paragraph 1 have unlinearity in range of 0,6%…3,0%. Gammamappers unlinearity was measured to be ±2,2% of maximum signal level. A sliding scale linearisation method described in [13] should improve devices linearity. Author plans to use this method in instruments next version.

7.2. Calibration of energy axis

An ionized particle falling into detector crystal causes a flash of light, amplitude of which is measured by the ADC of device. So a voltage reading characterizing energy of the particle is acquired. Gammamapper's ADC measures amplitude of input signal in range of 0..5V. In spectroscopy energy is the parameter researchers are looking for. So the next logical step was finding a formula (graph) characterizing the realtionship between channel number (voltage output by the ADC) and detected particles energy. This was done acquiring spectra of two samples with well known energies, in our case ^{60}Co and ^{22}Na.

For calibration coefficient calculations a caracteristic peak in spectra of ^{22}Na with 511 keV energy (see figure 7.5) and a peak in spectra of ^{60}Co with energy 1,33 MeV (see figure 7.4) were used.

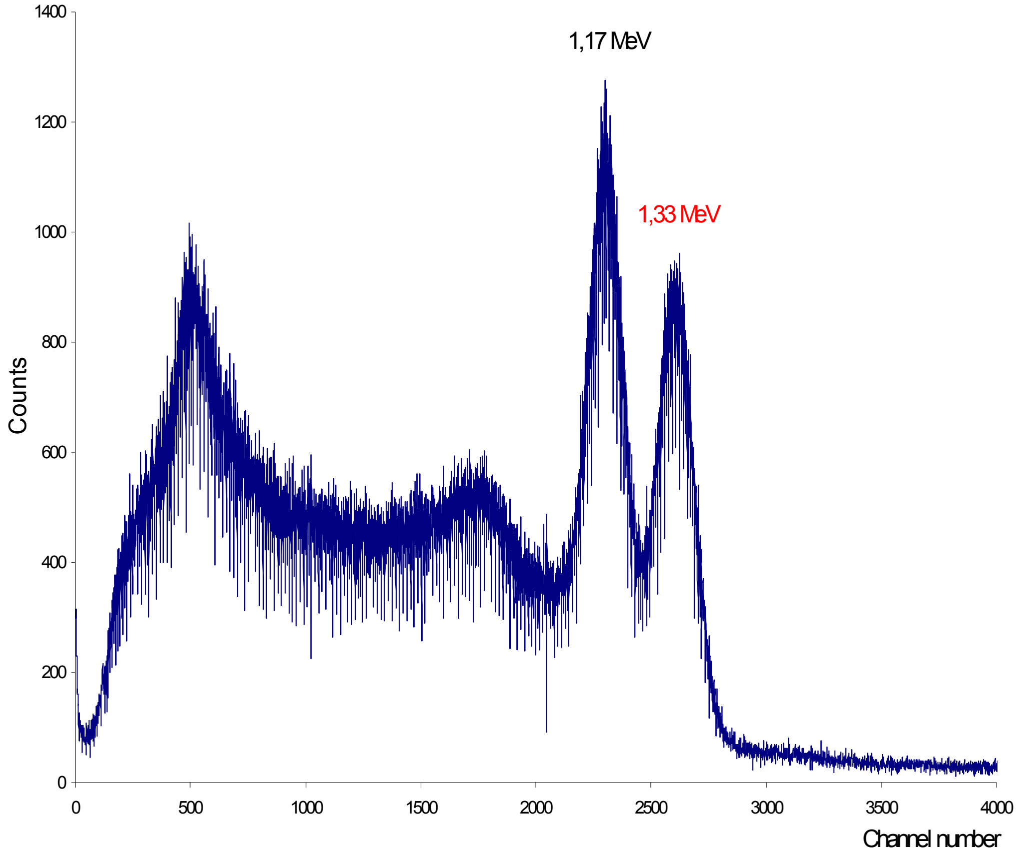

Figure 7.4. Spectra of ^{60}Co used for calibration coefficient calculations. Live time - 1h. Detector – Scionix's CsI(Ti)

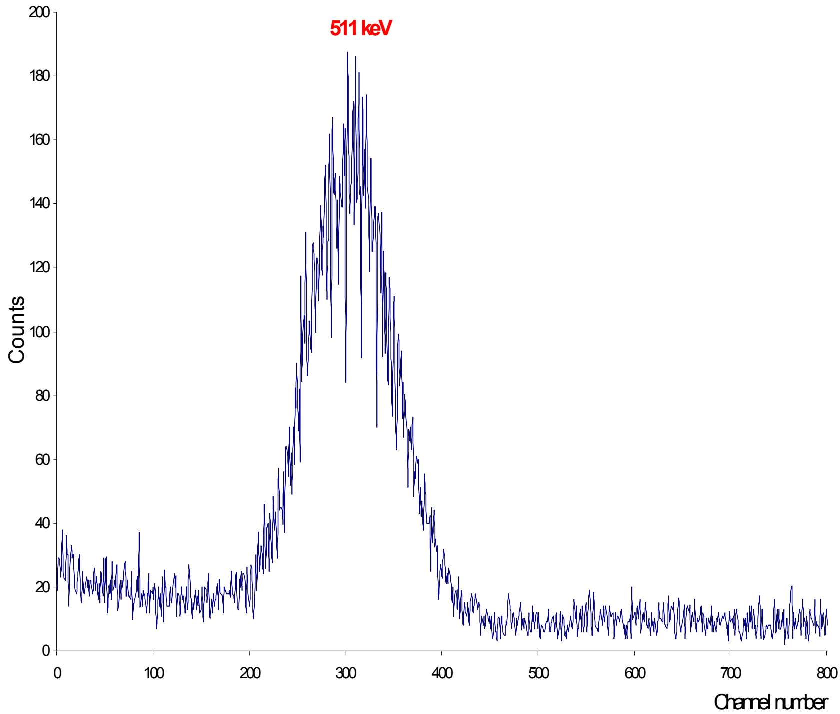

Figure 7.5. Fragment of ^{22}Na spectra. Live time - 1h. Detector – Scionix's CsI(Ti)

7.3. Test measurements with Scionix's CsI(Ti) detector

When the energy calibration was completed, it was interesting to test Gammamapper with some „real life“ samples. Firstly a spectra of KJ's water solution was measured (see figure 7.6). Peak of ^{40}K was found to have an energy approximately 1,46 MeV which agrees well with handbook data.

Next and perhaps most interesting step was finding out contents of street dust collected from Kiev. This city in Ukraine got a big amount of radioactive pollution that originated from the Chernobyl nuclear plant disaster in 1986. Resulting spectra revealed a caracteristic peak at energy of 662 keV (see figure 7.7). This showed that even after 23 years from the accident traces of radioactive ^{137}Cs could still be found in samples and probably in the city itself as well.

Well-defined peak at figure 7.7 made possible determining resolution of Gammamapper together with Scionix's detector. The resolution at energy 662 keV was found to be 7,5%. The result should be considered good and comes close to theoretical limit of this type of detector (see table 3.1).

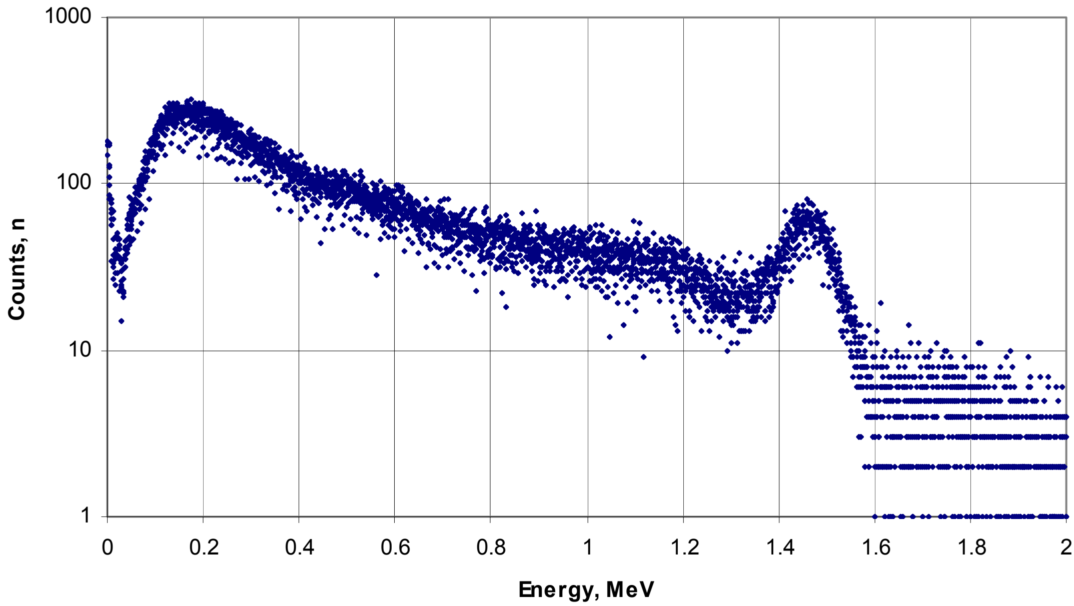

Figure 7.6. Water solution of KJ. Peak characteristic to ^{40}K at energy 1,46 MeV is clearly visible

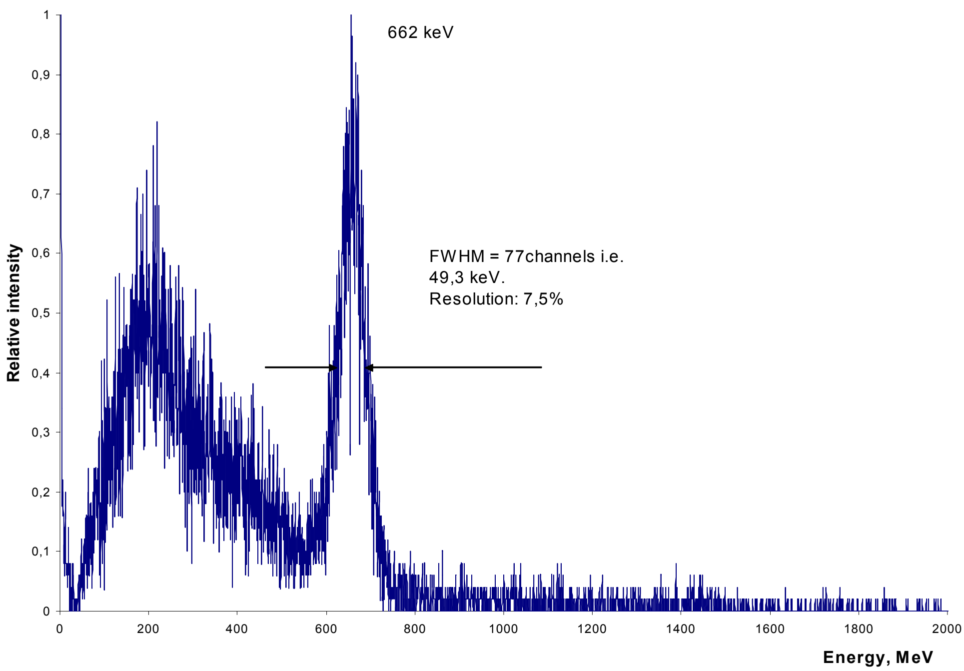

Figure 7.7. Spectra of street dust sample gathered from Kiev. A peak with energy 662 keV reveals presence of ^{137}Cs

Now the instrument was calibrated and ready for field measurements. Author conducted measurements with Gammamapper during two years. Instrument acquired spectra from locations author was every day for about 7..8 hours (until battery was exhausted). Luckily to the author no suspicious radioactive samples were found. Typical peak present in some spectras was ^{40}K. According to sources [24] this element can be found everywhere. Some typical spectras are shown on figures 7.8 and 7.9. Geographic map of measurement locations of one such „expedition" is shown on figure 7.10.

Determining activity of samples was not in range of goals set for the present work but „Gammamapper" enables such measurements also, provided we have sample sources with known activity. Unfortunately department of Physics of TUT does not posess such sources.

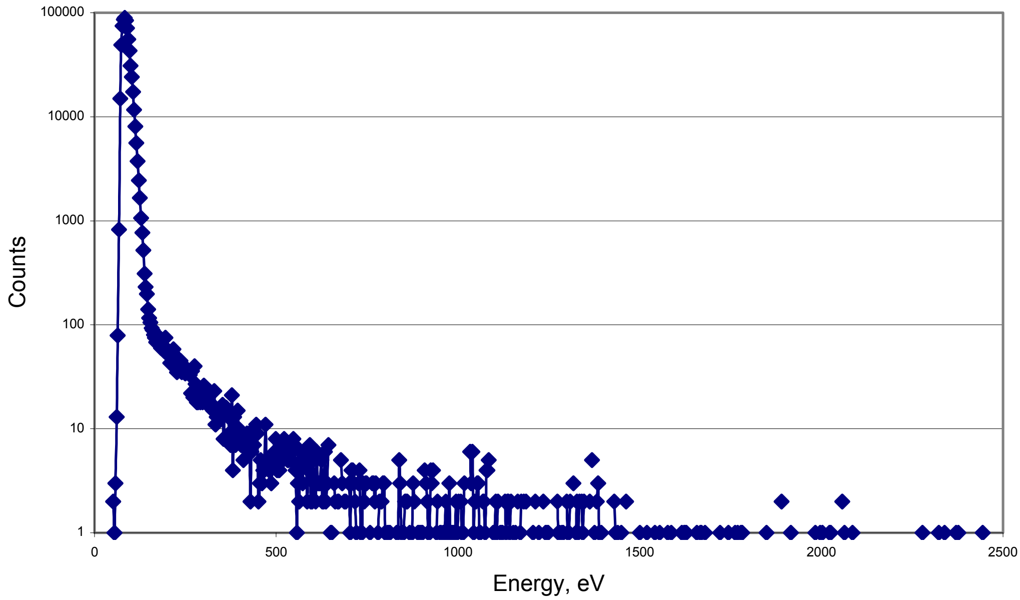

Figure 7.8. Typical spectra aquired on a small walk after working day

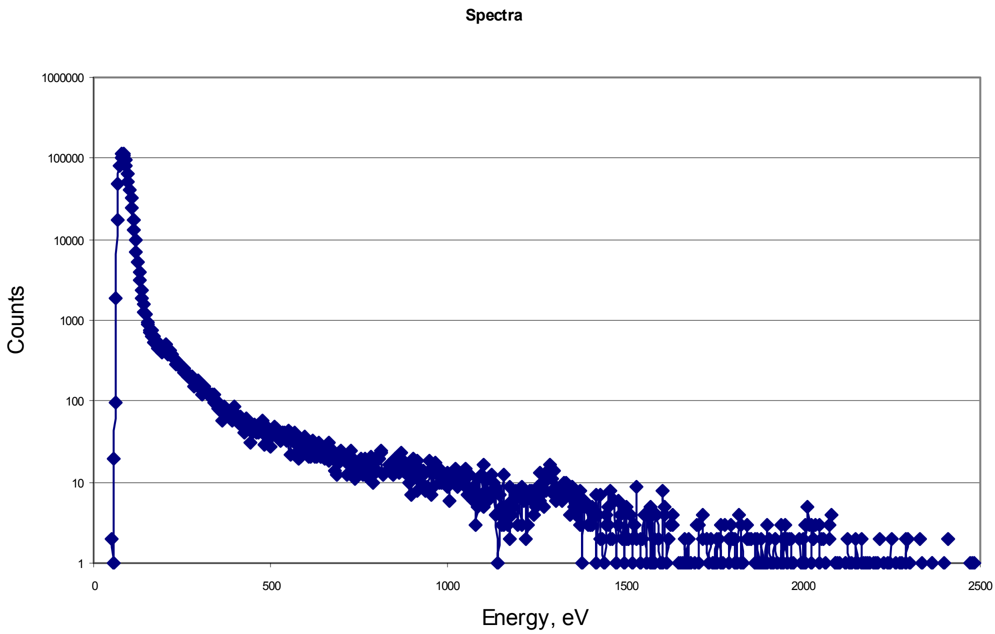

Figure 7.9. Spectra aquired en route to authors summer cottage

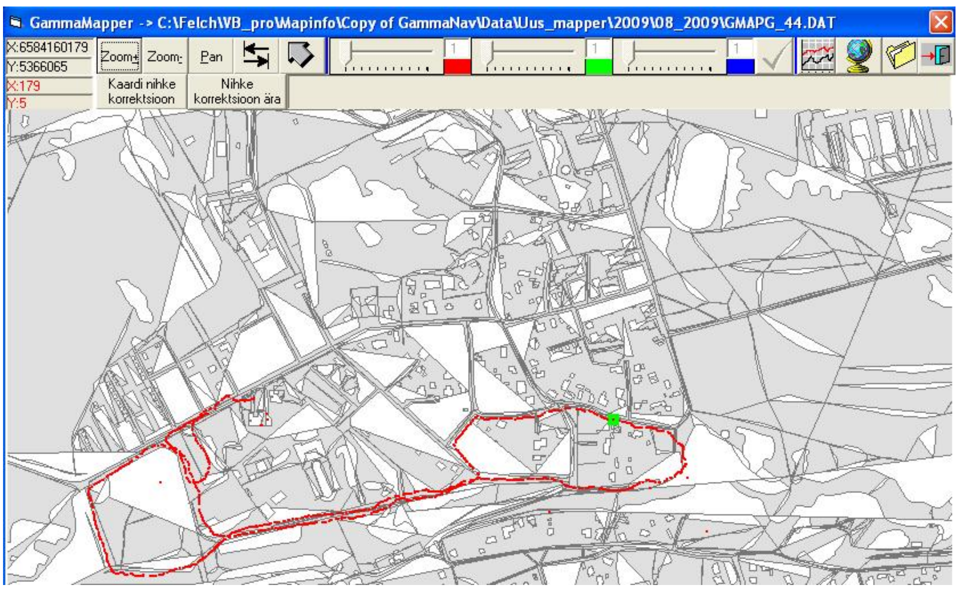

Figure 7.10. Gammamapper plots measurement paths on a geographical map

Main parameters of spectrometer prototype built in present work can be found in table 7.1

Table 7.1. Main parameters of Gammamapper

Property	**Value**
Analog to digital converter	Successive approximation type, resolution: 1024 channels
Pulse processing time	Conversion in ADC: 1,5 uS, owerall processing takes about 15 uS
Nonlinearity	2,2%
Upper- and lower level discriminators	Realized in firmware, level presettable in whole range
Memory	SD-card with capacity up to 4 GB
Live time	Up to 42949672 s, granularity 10 ms
Communcation interface	USB 1.0
Power supply	One 1,8 A/h LiIon cell (3,7V)
Maximum uptime	About 7,5 hours
Measures	
Weight	
Display	176*132 pixel color LCD
Detector	Scionix CsI(Ti) with bipolar output signal
Main processor	PIC18F4550 @ 24 Mhz
GPS engine	EM-406 with SirfStar 2 chipset
Time to get GPS lock	About 1 minute form cold start
Alarms	Audible,presettable to needed energy level or count rate
Navigation, data entrance	One multifunction navi key

8. Summary

Principles of work and schematic design of spectrometers for ionizing radiation were researched. Possible applications of such devices were discussed relying on data given in the literature. By analyzing the parameters of industrial designs the need for a portable spectrometer with somewhat wider possibilities for specific needs was established. A survey of the parameters of designs from well-known companies pointed out the minimum needs (linearity, amount of memory, number of ADC channels etc.) for the „Gammamapper" described in the present thesis. As a result such spectrometer with an embedded microcontroller was designed and built. Tests of the spectrometer built were carried out and their results were satisfactory. Additionally a program for downloading data from the device, visualisation of results and preliminary analysis of spectra was written. Photo of Gammamapper is given in fig. 7.1 and capture of the main window of the data analysis tool in fig. 6.3.

Although the parameters of Gammamapper are not bad, it must be pointed out that it is merely a prototype device. Research for improving the instrument is constantly going on. Not only the accuracy and other electrical parameters are going to be improved, but also some advanced functions will be added to spectrometer's firmware (automatic recognition of elements etc.).

Main results achieved in present work

- A compact battery-powered spectrometer for ionizing radiation was designed, built and tested. The device allows users to watch spectra on a built-in graphical screen module „on the fly" or after the acquiring process is over.
- Acquired data is automatically bound to geographic coordinates of locations where research took place. This is especially convenient if work is carried out from a fast moving vehicle. No known devices of this kind existed when this work was started.
- All measurement data is stored on a standard memory card. This overcomes the storage media limit present even in high-end devices like MCA-8000.
- Software written for the embedded microcontroller of the MCA includes functions of adding necessary measurement data and comments to the spectra as well as storing data locally and transferring it to a host computer. Software also enables marking locations of interest in the file and presettable

audible warnings. For user convenience a small low-power LED light source is built into the device.

- Gammamapper's firmware has a unique possibility to encrypt measurement results. This feature is used for protecting files against accidental erasure.
- For users convenience instrument defaults at start-up to a simplified mode not requiring any user input. Measurements are started with GPS enabled and data storage uncrypted.
- Utility program for downloading spectra from the instrument and storing them to a host computer was written. The utility also performs various kinds of data format conversions to enable importing Gammamapper’s spectral data to well known spectral analysis programs.
- A simple but unique device for testing GPS reception firmware was designed as a by-product of this work.

Described in the present study gamma spectrometer - data logger has been tested in operation for about 2 years. More than 5000 hours of data has been collected. Instrument showed good stability of parameters during test period. Figure.8.1 reveals the inside of authors prototype.

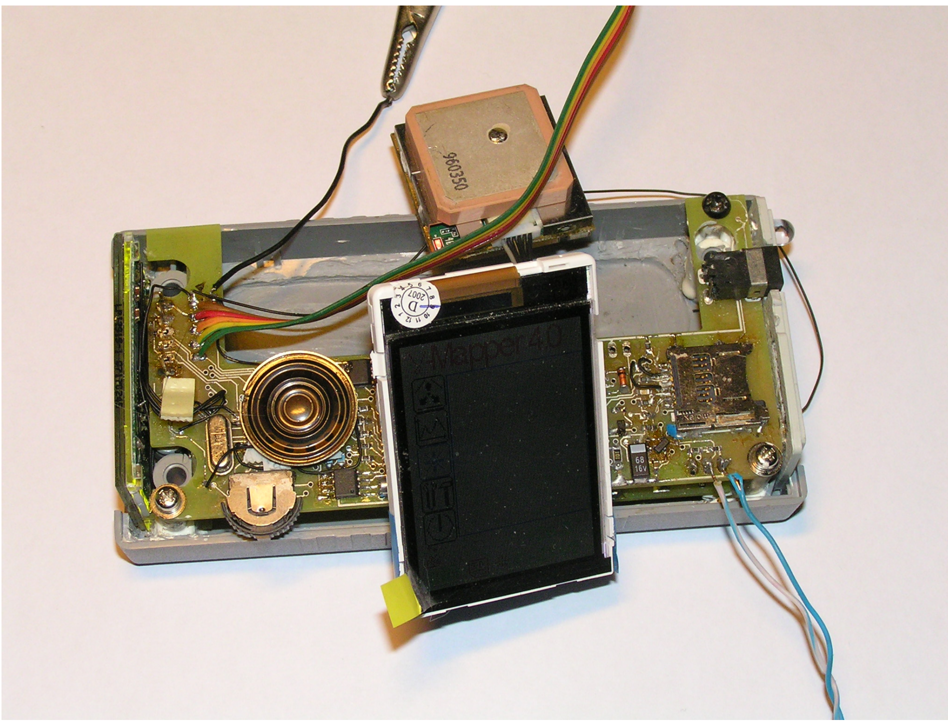

Figure 8.1. A glimpse to the inside of “Gammamapper“

Possible future improvements of „Gammamapper“ might deal with the following issues:

- scattering of peak voltage (presently about 3..5 channels) results should be minimized by means of lowering noise level generated by digital part of the instrument as well as by improving the peak detector circuit;
- bigger LCD screen and corresponding software for plotting spectra on it;
- possibility to display waypoints and geographic maps on instruments screen (the device has a built-in GPS receiver);
- touch screen instead of navi key to allow more convenient entering of comments to measurements;
- digital signal processor should replace traditional analog front-end circuitry;
- firmware should have a recognition algorithm for at least some commonly known (dangerous) elements (^{137}Cs etc.);
- device should draw marker lines for nuclides defined by user or fetched from database [39,41]. Nuclide data should be organised as one file on disk where device stores measured spetra.
- Spectrometer should have an interface for connecting to cellular phone. In this case it could use phones processor, LCD-screen, GPS engine and other equipment for better performance.

A new version of spectrometer with indicated improvements is presently being designed.

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Kokkuvõte
Portatiivne ioniseeriva kiirguse spektromeeter „Gammamapper“

Käesolevas väitekirjas on uuritud ioniseeriva kiirguse spektraalmõõtmisteks mõeldud mitmekanaliliste spektromeetrite parameetreid, võimalusi ja ehitust. On võrreldud mitmete juhtivate firmade valmistatud analoogseid seadmeid. Võrdlustulemuste alusel on valitud sobivad parameetrid ja välja töötatud ning valmis ehitatud autonoomse toitega portatiivne gammakiirguse spektromeeter „Gammamapper“.

Erinevalt muudest analoogsetest seadmetest „Gammamapper“:

- salvestab kogu mõõteinfo töötlemata kujul, võimaldadades tulemusi hiljem uuemate algoritmide alusel teisendada. Lisaks saab nii avastada lühiajalist viibimist kõrgendatud kiirgustasemega piirkonnas, mis muidu võiks märkamata jääda;
- andmed salvestatakse suuremahulisele standartsele mälukaardile, mis lubab mõõta kauem. Seniste spektromeetrite mälu on üsnagi piiratud;
- lisaks spektraalmõõtmistele salvestab seade GPSilt ka mõõtmiste toimumise kohtade geograafilised koordinaadid. Välja töötatud andmete visualiseerimise programm kuvab eksperimenteerija liikumise maakaardil;
- huvipakkuvate piirkondade kohta saab eraldi lasta kuvada spektri;
- spektri huvipakkuva piigi asukohta saab lasta otsida ja näidata kaardil;
- on võimalik lasta andmeid krüptida, samuti saab sisestada kommentaare mõõtmistingimuste jms kohta;
- seade on kaugjuhitav üle interneti, kasutades autori väljatöötatud protokolli ja juhtprogrammi. Sellest on täpsemalt juttu artiklis 5;
- lõpetamisel on otse „Gammamapperis“ spektrite „lennult“ ja hiljem failist kuvamise tarkvara.

Töö lõpuosas on toodud omavalmistatud spektromeetri katsetamise tulemused ning analüüsitud seadme edasise täiustamise suundi ja võimalusi. Töö käib hetkel seadme täiendatud versiooni kallal, mis ühenduks mobiiltelefoniga ja kasutaks selle võimalusi.

Abstract
Portable spectrometer for ionizing radiation „Gammamapper“

In the present doctoral thesis parameters, possibilities and design of multichannel spectrometer for measurementes of ionizing radiation are discussed. Properties of a number of similar devices from well-known manufacturers are compared to each other. Relying on this comparison best set of parameters was chosen for the device and the spectrometer was built.

Prototype spectrometer „Gammamapper“ built in present thesis has the following unique features:

- device records all measurement data in raw (unaltered) form on a standard SD-memory card. This approach lets experimenters use gathered data for new analysis using improved algorithms. Using a standard memory card gives nearly unlimited storage capacity. Earlier spectrometers stored data in onboard RAM with relatively low capacity;
- unaltered data format enables noticing passing areas with possible higher radiation levels that could otherwise be possibly filtered out;
- device records geographic coordinates of measurement plac(es) obtained from a GPS engine. Visualisation software shows movement of the experimenter on a geographic map;
- spectra could be plotted for the whole experiment as well as for selected regions of interest;
- visualisation software written for „Gammamapper“ locates peaks selected from spectra and shows regions where they were gathered on a geographic map;
- „Gammamapper“ can cipher measurements results using standard I-button as a key;
- device is remotely controllable over internet. A special protocol and program has been written for this purpose. More details about it could be found in [Article 5];
- firmware update enabling viewing spectra „on fly“ or from storage media on „Gammamapper's“ color LCD is presently being worked out.

Test results of the spectrometer built are given at the end of the present thesis. Possibilities of future improvement of the device are also discussed. Work on designing an improved version also suitable for use with cellular phones is presently going on.

LISA 1

ELULOOKIRJELDUS (CV)

1. Isikuandmed

Ees- ja perekonnanimi: Veljo Sinivee
Sünniaeg ja -koht: 7.12.1964, Tallinn
Kodakondsus: Eesti

2. Kontaktandmed

Aadress: Trummi 23a-7, Tallinn 12617, Eesti
Telefon: 50 666 24
E-posti aadress: felch@staff.ttu.ee

3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna 44. keskkool	1982	keskharidus
Tallinna Polütehniline instituut	1989	elektroonikainsener
Tallinna Tehnikaülikool	1999	magister

4. Keelteoskus

Keel	Tase
Eesti	Emakeel
Inglise	Kesk
Vene	Kesk
Prantsuse	alg

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
HP Color LaserJet kursus, 1994	AEL
„Intellektuaalomand teadus-ja arendustöös“, 2004	TTÜ teadus-ja arendusosakond
EAS'i projektide koolitus, 2005	TTÜ
Moodle kursus, 2007	TTÜ

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
8/1994…11/2003	Beesting A/S	remondiinsener
7/1989…praeguseni	TTÜ Füüsikainstituut	insener
1/2004...4/2007	Yoga-Intelligence OÜ	Elektroonikainsener
6/2007…	Silberauto A/S	Elektroonikainsener

7. **Kaitstud lõputööd:** Magistritöö „Portatiivne mitmekanaliline analüsaator ioniseeriva kiirguse spektraalmõõtmisteks “, Tallinna Tehnikaülikool, 1999
8. **Teadustöö põhisuunad:** kiirgusmõõteseadmed, digitaal- ja analoogskeemide disain ja ehitamine, seadmete protsessorite tarkvara kirjutamine
9. **Teised uurimisprojektid:** patenteeritud leiutise „Osavusmäng“ kaasautor
10. **Muud publikatsioonid:** Artiklid ajakirjades „Praktiline arvutikasutaja“ ja „Horisont“
11. **Hobid:** akvaristika, elektroonika, lendavad mudelid, programmeerimine

APPENDIX 2

CURRICULUM VITAE

1. Personal data

Name: Veljo Sinivee
Date and place of birth: 7.12.1964, Tallinn
Nationality: estonian

2. Contact information

Address: Trummi 23a-7, Tallinn 12617, Eesti
Phone: 50 666 24
E-mail: felch@staff.ttu.ee

3. Education

Educational institution	Graduation year	Education
Tallinn 44. secondary school	1982	secondary
Tallinn Polytechnical Institute	1989	Electronics engineer
Tallinn University of Technology	1999	master study

4. Language competence/skills

Language	Level
Estonian	Native tongue
English	average
Russian	average
French	Basic skills

5. Special courses

Period	Educational or other organisation
HP Color LaserJet course, 1994	AEL
Patent course, 2006	TUT
EAS's projets course, 2005	TUT
Moodle management, 2007	TUT

6. Professional employment

Period	Organisation	Position
8/1994..11/2003	Beesting A/S	Service engineer
7/1989..up to present	TUT Department of Physics	engineer
1/2004..4/2007	Yoga-Intelligence OÜ	engineer
6/2007..	Silberauto A/S	engineer

7. **Defended theses:** master degree thesis „Multichannel analyzer for ionizing radiation “, TUT, 1999
8. **Main areas of scientific work:** radiation measurement apparatus, design and building of various analog- and digital circuits, writing firmware for their embedded
9. **Other research projects:** coauthor of a patented device: „A new game of skill“
10. **Other publications:** Articles in journals „Praktiline arvutikasutaja“ and „Horisont“
11. **Hobbies:** aquaristics, electronics, flying models, programming

APPENDIX 3
Article I

V. Sinivee. A Simple Data Filter for the GPS Navigator. *Instruments and Experimental Techniques*, Vol. 49, No. 4, 2006, pp. 511–512.

ISSN 0020-4412, Instruments and Experimental Techniques, 2006, Vol. 49, No. 4, pp. 511–512. © Pleiades Publishing, Inc., 2006.
Original Russian Text © V. Sinivee, 2006, published in Pribory i Tekhnika Eksperimenta, 2006, No. 4, pp. 67–68.

APPLICATION OF COMPUTERS IN EXPERIMENTS

A Simple Data Filter for the GPS Navigator

V. Sinivee

Tallinn University Technology of Institute of Physics, Ehitajate tee 5, Tallinn, 12617 Estonia

Received September 28, 2005

Abstract—A GPS receiver–navigator is used as a data filter when measuring environmental parameters and referring them to the coordinates of the measuring point. The receiver is based on a PIC12F629 microcontroller (Microchip).

PACS numbers: 07.05.-t, 07.05.Hd, 07.0.Kf, 07.77.-n

DOI: 10.1134/S0020441206040105

When measuring environmental parameters, e.g., radiation level, gravitational acceleration, etc., the results of measurements must often be referred to the coordinates of the measuring point. A conventional method is to perform measurements on a grid of points with predetermined coordinates. However, this is sometimes inconvenient, especially when measurements are taken while moving. A solution to this problem may be to use a GPS receiver–navigator. Modem GPS receivers are characterized by small sizes and low power consumption and can be easily combined with battery-powered portable measuring equipment. For example, using a mobile dosimeter and referencing the data to the coordinates of the locality and to the astronomical time allows one to accurately determine where and when a certain radiation dose has been received.

This work presents a referencing system of this type, which operates in conjunction with a portable multichannel ionizing-radiation spectrometer, based on a CsI(Tl) scintillation detector (Scionix). The results of measurements, coordinates, and time data are recorded into a CF memory card, from which the data can be transferred into a personal computer. The spectrometer uses an RISC processor from Microchip. Since the RISC processor is continuously busy when gathering data, a separate simple and low-cost PIC12F629 controller (Microchip) is used to ensure the GPS functions.

The navigator is based on a JP-7 GPS receiver from Falcom (http://www.falcom.de/index.php?id=314). This receiver outputs data via the RS-232 interface; details of the data-transfer protocols are available from http://home.mira.net/~gnb/gps/nmea.htm. A program filter is used to extract the required data from the data stream (only coordinates and time are usually of interest). The filter program can be run on the controller of the measuring instrument itself, if the instrument's resource is sufficient, or on a simple additional controller, as in this case.

ALGORITHM

The PIC12F629 controller monitors the output data stream from the GPS receiver and extracts messages starting with the sequence of characters $GPRMC. Here is an example of a GPRMC-protocol sentence:

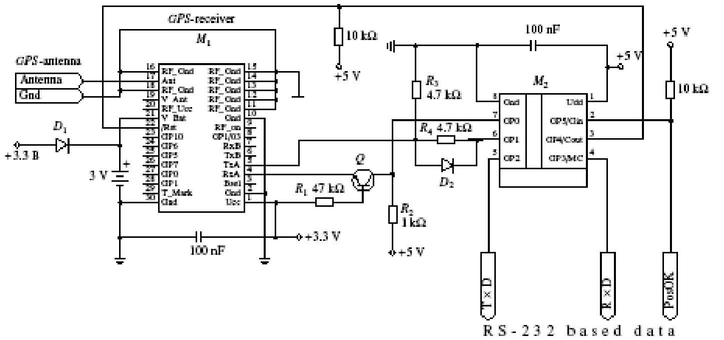
$GPRMC,081836 A,3751.65 S,14507.36 E,000.0, 360.0, 130998, 011.3, E*62
Name time coordinate coordinate speed course date magn.variat. sum

Upon detection of this sequence, the program enables writing of the selected fields (coordinates and time) from the incoming data (on the condition that character A is present in the third field, which confirms the data validity). To improve the transmission reliability, check summing may be used; however, the experiments showed that this is unnecessary.

Pin *2* of the PIC controller (GPIO.5) serves a dual function: (1) to indicate (with a high level) that the data are available and (2) to allow (with a low level) the host controller to disable data transfer if the controller is busy.

Pin *3* of the PIC controller (GPIO.4) is used to restart the GPS receiver after turning on the power or in the case of a transmission error.

The filtered data are transmitted via pin *5* of the PIC controller (GPIO.2) at a rate of 4800 bd. The data sequence contains the start-of-sequence character "$"; 28 bytes representing the coordinates, time, and date; and end-of- block character 0x0D (hex). Other fields of



Schematic of the GPS data filter: (M_1) JP7; (M_2) PIC12F629; (Q) BC847C; (D_1) PRL5818; and (D_2) LL4148.

the GPS-receiver output can also be selected when needed.

CIRCUIT AND COMPONENTS

Since the GPS receiver and the PIC controller require supply voltages of +3.3 and +5 V, respectively, circuits R_1– R_2– Q_1 and R_3– R_4–D_2 (see the figure) are used to adjust the signal levels.

After the GPS receiver is turned on, it may take up to 45 s to obtain a new fix; this time will be much shorter if the coordinates of the previous position are stored. A storage battery, trickle-charged through diode D_1 during operation, can be used for this purpose. In the unit under consideration, no data saving is required, and, when it is turned on, the PIC controller resets the GPS receiver.

The use of a double-sided printed-circuit board and discrete components allows the unit to be compact and easily built into portable instruments.

The source code, compiled code, and schematic are available as a single archived file from http://parsek.yf.ttu.ee/~felc/gps.zip. The program or parts of it are free under the terms of the GNU General Public License.

APPENDIX 4
Article II

V. Sinivee. Gammamapper – a prototype gamma spectrometer-data logger.

GAMMAMAPPER - a prototype gamma spectrometer-data logger

V. Sinivee MSc
Department of Physics
Tallinn University of Technology
Ehitajate tee 5
19086, Tallinn, Estonia

Keywords: ionizing radiation, spectrometer, data logger, encryption, , Vernam cipher, GPS, geographic coordinates, FAT.

Abstract **In present study a portable autonomous gamma spectrometer-data logger is described. Device records all measured gamma events separately and binds data to geographic coordinates using a GPS engine. Data is stored on standard memory card with FAT file system. Device offers data protection by encrypting files. A standard I-button works as a key.**

I. Introduction

Ionizing radiation sources can be found in a wide range of occupational settings, including health care facilities, research institutions, nuclear reactors and their support facilities, nuclear weapon production facilities and other various manufacturing settings. These radiation sources can pose a considerable health risk to affected workers if not properly controlled. From the point of view of the occupational exposure, the radiation dose is a very important measure. But limiting only to measuring dose does not necessarily give enough information about possible hazards. Measurement of the energetic spectra of the radiation source allows distinguishing which isotopes cause the radiation, in what state is the source, whether the contamination of water or tissues occur, etc.

Recorded spectra are sometimes filtered, and the averaging nature of this process may mask short rises of radiation level (e.g. passage through a strong source).Therefore it is desirable to record separately every pulse output by the radiation detector and analyze data later. This method is not very suitable for the investigation of highly active radiation source since it produces too much data. In environmental research possible radiation sources are different and compatible to worked out method.

When studying environmental radioactive pollution, it is essential to have the measurement data binded to geographic coordinates. Nowadays a GPS-receiver is a handy tool, especially if the data should be collected from a moving vehicle.

Present study describes a prototype gamma spectrometer-data logger – "Gammamapper" – designed and built in Department of Physics of Tallinn University of Technology. The device is equipped with a CsI(Ti) scintillation probe and spectroscopic amplifier from Scionix. Every pulse output by the amplifier is captured by a peak detector, digitalized and stored on a memory card using standard FAT file system. Instrument's main processor tracks geographic coordinates received by GPS engine. A separate low-cost micro controller prefilters GPS's output stream looking for certain messages only. This "filter" also keeps track on the validity of geographic data and double-buffers it [1].

The main processor of the spectrometer protects the measurement results by encrypting of data.

II. Data Protection

Sometimes the results of experiments should be kept protected. Protection may include disabling accidental erasure of files and, even restricting access to files.

Traditionally protection is carried out in computers, where experiment data is stored. Encrypting algorithms are complicated but fast and very reliable.

Modern digital instruments offer many side-functions: they perform preliminary analysis of data, log measurements etc. Nevertheless these devices do not provide proper data protection. This is very important when sensitive results are treated (e.g. medical instruments or investigation of a crime scene).

Encryption is one solution to this kind of problem. The best solution is when the measuring device encrypts all data. In this case it is possible to protect encrypted files from accidental erasure also.

III. Block Diagram of "Gammamapper"

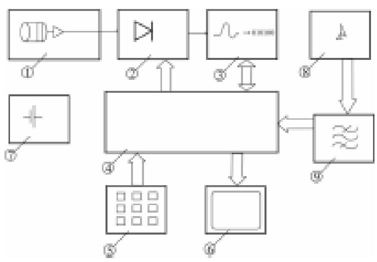


Figure. 1. "Gammamapper's" block-diagram. 1 – gamma sensor, 2 – peak detector, 3- analog to digital converter, 4 – mikro controller, 5 – keyboard, 6 – LCD display, 7 – power unit, 8 – GPS engine, 9 – GPS data filter.

Spectrometer uses Scionix's off-shelf gamma sensor (1) with built-in spectroscopic amplifier (see Figure.1.). This CsI(Ti) probe has compact size, improved ruggedness and significantly lower power consumption compared to standard designs implementing NaI(Ti) scintillation detectors and PMT tubes. Scionix's state-of-art sensor provides a bipolar semi-gaussian output signal with total pulse duration of 15 µs. Energy resolution measured at 662 keV is 8,7%.

Sensor's output pulses are fed to a peak-detector (2) built around fast operational amplifiers by Linear Technology. Detector is reset after every successive digitalization of input pulse.

Successive approximation type analog to digital converter (3) converts captured pulse's amplitude to digital form. This signal is handled by unit's controller.

Measuring process is controlled and all necessary conversions are carried out by firmware running on a standard off-shelf micro controller (4), manufactured by Microchip. This microprocessor has low power consumption and rich set of on-chip peripherals.

Control code also handles storing measurement data to compact flash or multimedia card. Standard file operations like deleting, viewing and moving are supported.

In order to reduce noise, controller is put asleep for most time of acquiring spectra. Every captured and digitalized pulse wakes it up and calls a short routine storing the event. If a preset count of pulses is reached, instruments encrypts data block (if encryption is enabled). After that it is saved on storage media. At the same time keyboard (5) is scanned and information display (6) showing progress of the experiment is refreshed.

Since spectrometers front end is a classical analog circuit, specific methods have to be employed to improve analog to digital converters differential and integral linearity specs. In present device a sliding scale linearization method suggested in [5] has been implemented.

Spectrometer uses a temperature sensor from Dallas to compensate drift of readings due to ambient temperature changes. Sensors readings are stored with spectral data to the same file. This approach should enable recalculating and correcting once measured spectral data in case a better correction algorithm is found.

When charge level is low Gammamapper's power unit (7) automatically terminates measurements. In that case to prevent loss of data and corruption of storage media's file system, all open files are closed. A special flag is set in files supplementary info area to notify premature termination of measurements.

After every preset amount of handled gamma events the spectrometer reads and stores geographic coordinates from a GPS engine (8). The engine (manufactured by Falcom) has been built on a new generation SirfStar III chipset with low power consumption and excellent sensitivity.

A separate low-power micro controller (9) filters GPS's data stream separating useful and valid information.

Measurement data files are transferred to a host computer for further analysis via micro controllers' built-in USB channel. The device has a special working mode where it outputs a block of data right after it has been collected. This mode in conjunction with special program is already used for teaching purposes.

Gammamapper's firmware also permits encrypting every single amplitude of incoming pulse "on the fly". High-speed operation and compact code of the device is achieved by using assembly programming language.

IV. Crypting data

Scientific instruments can produce results at high speed. Therefore an encrypting algorithm should be compact and fast. One possible solution is to apply a Vernam cipher [2]. According to some authors [3, 6, 7] it is the only currently known unconditionally secure cipher that provides truly random key

There are many ways to generate crypto key. It is possible to use keypad to input the key, or read it from some kind of external memory etc. In this work a standard and widely spread memory key "I-button" producing 64-bit unique number was used [4].

As a result the input crypto key obtained following qualities:

- convenient – user does not have to remember or write down any numbers;
- fast – I-button can communicate with speed up to 16 kBits/s;
- cost-effective – I-button is widely used in various electronic phonolocks and easily available;
- power consumption - is reduced to minimum; the button derives power from data-line and only during reading. It is very economic in a battery-powered instrument.

In this prototype instrument data is saved on a CF- or MMC disk with sector length of 512 bytes. The process of ciphering data in "Gammamapper" is presented in Figure.2. While the processor of a spectrometer has collected a certain amount of results, a Vernam-cipher subroutine is called and the result is written to disk. This approach permits to carry out measurements at full speed. Only an additional small delay due to ciphering during disk write operations occurs.

File system of the spectrometer demands inserting a key (I-button) every time a new measurement is started (key is stored into RAM-memory) and also in case if an attempt is made to delete encrypted file. This should minimize the risk of accidental erasing valuable data files.

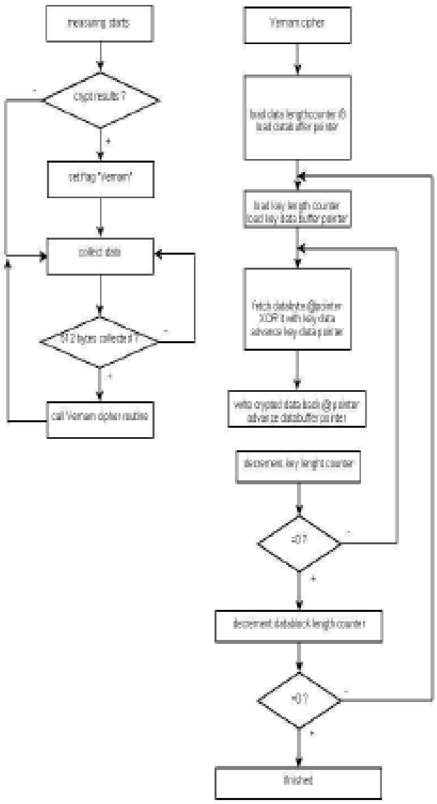


Figure. 2. The Vernam cipher flowchart

V. Pc Program

To support this system a small utility for visualization and analysis has been written. Figure.3. shows utility's working screens. This program uses Windows platform and allows plotting measured data onto geographical maps. To save computer memory only needed map quadrants are loaded. As the heart of utility's map engine a free GIS environment – Map Window GIS is applied..

On map user can select regions for which gammaspetra will be plotted. For better visualization on map waypoints can be colored according to energy of gamma particles what are detected in these points.

The spectra viewing tool of the program allows to add or subtract spectra (i.e. subtracting background) and format conversions for exporting data. It is helpful if more powerful analysis programs are used.

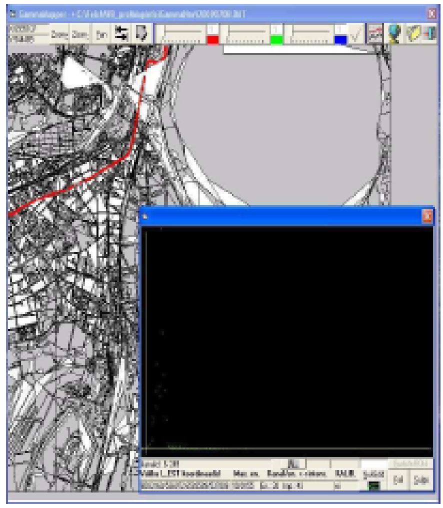


Figure. 3. The screen of Data analysis tool.

VI. Conclusion

Described in the present study a Gamma spectrometer-data logger has been tested in operation for about a year. More than 5000 hours of data has been collected. Instrument showed good stability of parameters during test period. Figure.4. reveals the inside of authors prototype.

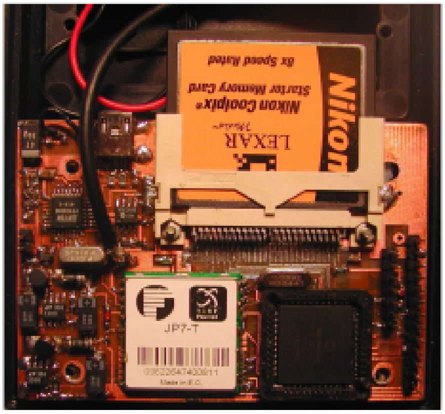


Figure 4. A glimpse to the " inside of " Gammamapper.

Testing showed that possible future versions of the device should include:

- bigger LCD screen and corresponding software for plotting spectra on it;
- possibility to display waypoints on instruments screen since the device has a built-in GPS receiver;
- touch screen instead of keypad to allow more convenient entering of comments to measurements;
- digital signal processor could replace traditional analog front-end circuitry.

A new version of spectrometer with indicated improvements is presently being designed.

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APPENDIX 5
Article III

V. Sinivee, L. Kurik, U. Kallavus. Combined Positioning System for Mapping Measured Properties of Objects of Arbitrary Shape. 6th International DAAAM Baltic Conference „INDUSTRIAL ENGINEERING“ – 24–26 April 2008, Tallinn, Estonia.

6th International DAAAM Baltic Conference
"INDUSTRIAL ENGINEERING -
24-26 April 2008, Tallinn, Estonia

COMBINED POSITIONING SYSTEM FOR MAPPING MEASURED PROPERTIES OF OBJECTS OF ARBITRARY SHAPE

Sinivee, V.; Kurik, L. & Kallavus, U.

Abstract: *In material science and environmental research it is essential to have the measurement data binded to spatial coordinates. In industry same need arises in transferring measured (quality determining) key-properties of details with complex shape to a CAD model. A GPS-unit could be used for positioning but unfortunately in many cases the spatial resolution is not satisfactory or satellite signals are not available. Resolution problem is critical in case of mapping material parameters of small objects where location errors even in range of some centimetres are intolerable. In such case photogrammetric system for 6 DOF positioning could be used. Combining GPS and photogrammetry gives universal method for determining exact location of measurement points.*

In present study handheld semi-automatic combined GPS and photogrammetric positioning system for data collecting and recording is described.

Two examples of implementing described idea are given. In first case experiment data comes from a microwave moisture content measuring instrument "Moist 200". In second example analogous system is used in an experimental gamma spectrometer.

Keywords: GPS, 6 DOF positioning, photogrammetry, mapping material properties.

1. INTRODUCTION

Large amount of different specialized instruments exist for measuring parameters of materials. In troublesome but unfortunately frequently met case when object of interest is not uniform and spatial distribution of some parameter must be found, the exact location of measurement points must be determined. In case of real world objects this may not be a simple task.

Various positioning systems implementing usually active beacons working in the ultrasound, radio-, or IR-bands are available. Exact position of object of interest is given as a function of distance from the beacon. Using such systems means that beacons exact position must be known with high precision. Signal echoes and objects blanking beacons are severe problems when working with such systems. At least 5...6 beacons must be "visible" to the system to guarantee required accuracy. Increasing number of beacons is highly recommended.

Using active beacon stations usually means that cost of the positioning system can not be very attractive. Typical example of such kind of system is GPS (Global Positioning System). GPS is fairly good developed system and suits well for determining objects geographical coordinates. Unfortunately positioning error of widely used GPS-engines is limited to 5...20 meters in horizontal direction (resolution is even worse in vertical direction).

GPS is useless indoors or in other places where satellite signals can not be received. Earth-bound transponders could be added to GPS system and they improve overall resolution and signal availability but there are some restrictions in their use and in some countries transponders are prohibited due to causing interference to other GPS

receivers. Above mentioned systems are not able to determine objects spatial orientation which could be very important in some case (e.g. when determining source of moisture or some kind of radiation).
Available laser tracking systems lock on objects following constantly their direction and position. Problem of other (big) objects veilding our object of interest form tracking system remains however. Unfortunately available laser tracking systems do not give information about tracked objects spatial orientation.
Close range photogrammetry has developed exceptionally rapidly latterly and has become popular. It offers good spatial resolution of objects. Only a digital camera and special software are needed.

2. SYSTEM DESCRIPTION

2.1 Previously used system

A 6 DOF photogrammetric positioning system for measurement probe is described in paper [1]. Photogrammetric software locates object's relevant spatial points analyzing ordinary digital photos taken from object of interest. Connecting those points with lines and/or surfaces a photorealistic model suitable for most CAD-programs could be built. Coded targets placed on the scene before taking snapshot is used to help automation of the process and improving resolution. Camera stations exact spatial position and orientation in each image file is needed for calculations. This fact could be used to determine measurement probes position. Connecting camera and probe mechanically makes latter's position also fixed [1]. Relevant components of the system together with related coordinate system are shown on fig.1.
In many cases measurement probe is connected to it's control unit using proprietary protocols and/or connection schemes thus making automatically binding measurement results and snapshot files (for 6DOF photogrammetry) difficult.

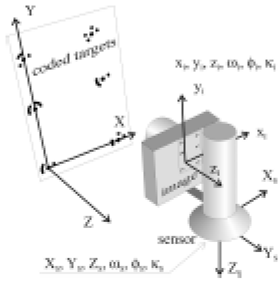

Fig. 1. Components of a 6 DOF photogrammetric system [1]

Modern sensors possess digital output making connections between probe and camera more universal.
Main drawback of the system is absence of inflexible association between snapshots taken from the object and measurement results introducing possibility of human errors. In case of outdoor measurements geographic coordinates of measurement place are also relevant. GPS can be used to determine measurement areas coordinates roughly using photogrammetry values for high-resolution positioning.

2.2 Improved system

Main idea of the improved 6DOF positioning system is combining high accuracy of photogrammetric positioning and globality of the GPS system with automated synchronizing of measurement results read from probe with corresponding image files. In order to accomplish above described tasks, a relatively simple controller has been designed and built (see fig. 2). The device plugs in camera's memory card slot. CF-card itself goes into controller's connector. Described approach lets controller listen to communication between camera and memory card and makes intercepting the card and reading/writing data to it possible. For outdoor measurements geographic coordinates of experiment's place are often needed.

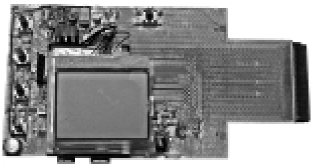

Fig. 2. Controller board

To provide them controller board equipped with a small OEM-GPS engine built around new SirfStar III chipset featuring low power consumption and excellent sensitivity.
A small information display and keyboard enables user configure the experiment. For example one can choose to save measured data into image file's EXIF-data portion. In case of only one numerical result per image the result could also be added to image-file's name. Configuration screen also makes possible choosing different fields to be saved from GPS-engine's data stream.
The controller has one SPI-port and one standard RS232 port to read measurement data from various sensors or measuring devices (see Fig. 3).

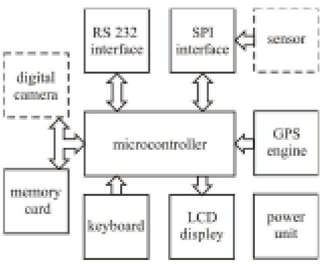

Fig. 3. Controller's block-diagram.

Measuring process is controlled and all necessary conversions are carried out by firmware running on a standard off-shelf microcontroller manufactured by Microchip. This microprocessor was chosen due to its low power consumption and rich set of on-chip peripherals.
Control code also handles storing measurement data to camera's compact flash card. Standard file operations and long file names are supported.
Measurement cycle is initiated by pressing camera's trigger. It then takes a snapshot and stores image to memory card. This event is recognized and monitored by circuits controller chip. Right after camera has finished writing operations, controller pulls cameras Card Detect line high in order to get control of the card. According to experiment configuration it then saves geographical coordinates received form GPS engine to image file or, if configured accordingly, to a separate file. Next step involves communicating with measurement sensor(s) and reading their results which will be saved next to geographic data.
Described process takes no longer than 1 second after which memory card is released for camera control again.

2.3 Data processing

Result of measurements is a set of image files containing numerical value(s) of data from probe(s). Mentioned values are stored in exif-data area of image files (or added to the filename). Possible GPS data is stored likewise. Next step includes processing all image files in order to recognize coded targets and find camera stations. For this purpose we use commercially available software "PhotoModeler Pro". This software is designed mainly for creating 3D models of real world objects and for image based measurements (length) but suits well for our application. "PhotoModeler" combines the image data and locates coded targets in three dimensions. At the same time software calculates image location (x_i, y_i, z_i) and spatial orientation (Euler angles □;□□;□□;) for all camera positions. "Photomodeler" uses right hand coordinate system. To achieve good project quality one must take care that all targets are well binded together. For that reason additional photographs must be taken from different directions to catch more targets to one picture and to guarantee good overlapping of taken pictures. Unfortunately experiments show that some targets are not located well enough by software and we must manually correct data processing routines or delete some poorly defined camera stations. Data processing result is a table with image filenames, camera stations coordinates and orientations with some quality parameters - number of reference points, largest and RMS residual (pixels). To find rotation matrix and transition vector for transforming image coordinates to sensor coordinates we are using photogrammetric method described in article [1]. An Excel worksheet is composed to help automated calculation of coordinates and spatial orientations of sensors. Previously we must define sensor coordinate system. If results of material properties measurements are stored into image filename, then location information and measured values are in the same Excel table. For reading Exif additional software is needed. Results are exportable to CAD programs for visualizing or further processing.

3. SAMPLE APPLICATIONS

3.1 Moisture contents measurements

Using described method in measuring moisture contents of materials has no principal restrictions except the fact that measuring probe should not be significantly smaller than camera used for snapshots.

First application example is 3D mapping of moisture content of materials under investigation with aquameter using microwave reflections from water molecules. Industrial probe "Moist 200" inflexibly attached to camera is directly connected to controller board ("Moist 200's" native control unit was expelled from described setup).

A „ Canon PowerShot A95" camera was used for shooting images due to it's "vary angle" screen. Since the 30 cm range moisture sensor uses polarized microwave radiation, it is essential to determine probe's spatial orientation. For example if the tested sample/object has a fibrous structure, results depend much of sensor's rotation angle around its longitudinal axes. Described effect is clearly visible when measuring, for example, moisture of paper.

Camera's flexible viewfinder gives operator convenient control over the scene.

For testing system possibilities and accuracy we placed objects with known geometry into a 3D test-field (see fig. 4). Accuracy and repeatability of probes calculated coordinates X_S, Y_S, Z_S was better then 1 mm for majority of measuring points. Some points however had a positioning error even as large as 1 cm. Analysis of results showed that reason for positioning errors was too small number of coded targets in camera's view. Experiments pointed out that at least 7…8 well located targets are needed for accurate positioning. Targets should not be placed too close to each other. Spatial orientation uncertainty was estimated indirectly knowing camera's viewing area and uncertainty of target's positioning. Estimated uncertainty was approximately one minute for given camera. For moisture content measurements this result is very good – moisture sensors measurement volume reaches up to 40 liters.

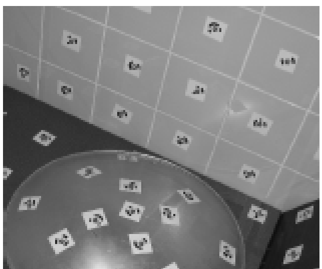

Fig. 4. Test-field with coded targets

Further improving of positioning accuracy is possible by using cameras with higher resolution. Positioning accuracy up to 0.1 mm for 3 m object (accuracy 1/30000) could be reached with 11 mega-pixel cameras [3]. Retro-reflective targets could be used to improve contrast of targets located far away from camera. In described test GPS data was not needed. In real life moisture content measurements geographical coordinates could be very important. Obtaining geographical coordinates of sensor locations from GPS and then using photogrammetric method for determining coordinates of measurement points in local coordinate system, makes calculation of orientation of local coordinate system relative to geographical coordinates possible. Results positioned as described could be entered into some bigger geographical information system (GIS). For example one could show moisture content measurements results of some building's walls in Google Earth-like 3D map.

3.2 Gamma mapping

In environmental research like in field-measurements of gamma radiation, it is usually enough to have geographic coordinates of measurement place(s). In case of finding object that requires further exploration, probably with better spatial resolution, above described photo-grammetric positioning system is used. Co-author of present thesis uses similar circuit and working principle to record gamma radiation in a portable autonomous gamma spectrometer called "Gammamapper" (see fig.5). In this device amplitude of pulses output by CsI(Tl) gamma sensor is constantly measured and results are written to memory card. Additionally geographic coordinates of measurement place together with ambient temperature are saved to the same file. Computer software displays path (if experiment was carried out not in one place) and acquired gamma spectra (see fig. 6).

Fig. 5. A glimpse to the "inside" of Gammamapper.

Improved version of the device enables operator to view acquired spectra and geographic map of the experiment right on instruments LCD screen. Several other options like elementary analysis of acquired spectra and improved graphical user interface are implemented. A communication port for connecting to above described 6DOF photogrammetric positioning system has been added. Since spatial orientation of gamma probe is usually not very important, system is even more simple than the one in moisture measurement example. Properties of "Gammamapper" were more thoroughly discussed in CISSE 2007 conference [2].

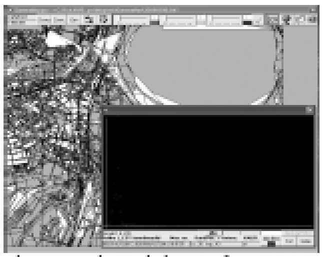
Fig. 6. Main window of "Gamma-mapper's" software shows path where measurements were carried out and a spectra analysis window displaying (luckily!) only usual background radiation.

4. FUTURE DEVELOPMENTS

Universality of connecting different parts of described system should be improved. Widely used USB port and Bluetooth devices could help solving the problem. Using a camera with built-in GPS engine or mobile phone with camera should be a perspective solution.
A software development kit (SDK) based open-source operating system Android [4] has been developed by Google. This SDK is specially designed for development of software for mobile systems.
Freely available project called Android could ease further development of positioning system described in present thesis.
Using Bluetooth-enabled sensors makes synchronizing measurement results, geo-coordinates from GPS-engine and image files from camera possible with software only.

5. CONCLUSION

Existing systems binding geographic coordinates form GPS engine with local coordinate system used for measuring parameters of objects are either expensive (such as total station) or lack positioning accuracy (e.g. various ultrasonic devices).
Use of those systems may be restricted in case of limited space or objects with complex shape. Usually measurement probe's spatial orientation can not be determined.
Proposed in present thesis solution which combines digital camera, measurement probe and GPS receiver in one instrument enables mapping of measurement results in 3D-space with high accuracy. At the same time it requires only simple widely available means. Orientation of measurement probe is also determined.
An important improvement is saving results of measurements and positioning information in one file thus leaving no room for human errors.
Flexibility of photogrammetric method makes no constraints to range of experiment provided the coded targets have suitable dimensions. Size of digital camera could be important in some cases.
Results of measurements can easily be exported to CAD-programs.

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7. ADDITIONAL DATA ABOUT AUTHORS

Veljo Sinivee, Tallinn University of Technology, Department of Physics, Ehitajate tee 5, 19086 Tallinn, Estonia, felch@staff.ttu.ee, phone +372 620 3004
Lembit Kurik, Tallinn University of Technology, Department of Physics, Ehitajate tee 5, 19086 Tallinn, Estonia, lkurik@staff.ttu.ee, phone +372 620 3003
Urve Kallavus, Tallinn University of Technology, Centre for Materials Research Ehitajate tee 5, 19086 Tallinn, Estonia, urka@staff.ttu.ee, phone +372 620 3152

APPENDIX 6
Article IV

V. Sinivee, L. Kurik, U. Kallavus. Mobile photogrammetry for positioning measuring sensors.

Mobile photogrammetry for positioning measuring sensors

V. Sinivee[1], L. Kurik[2], U. Kallavus[3]

[1] Department of Physics, TTU, Ehitajate tee 5, 19086 Tallinn, Estonia, E-mail: felch@staff.ttu.ee
[2] Department of Physics, TTU, Ehitajate tee 5, 19086 Tallinn, Estonia, E-mail: lembit.kurik@.ttu.ee
[3] Centre for Materials Research, TTU, Ehitajate tee 5, 19086 Tallinn, Estonia, E-mail: urko@staff.ttu.ee

Spatial coordinates of measurement sensors are needed to map measurement results. One solution for determining coordinates is photogrammetric method using a cell phone with good resolution digital camera rigidly attached to measurement sensor. Photogrammetric software calculates coordinates and spatial orientation of sensor(s) from taken photographs. In order to achieve good accuracy and automation, coded targets are used.

Standard off-shelf components that are readily available nearly in every electronic store are used in described system in order to ease implementation of proposed method and reduce costs. Sensors and main unit (cell phone) talk to each other via Bluetooth radio link. Acquired measurement results are binded to measurement point's coordinates and could be processed later with various CAD programs.

1. Introduction

Determining exact coordinates of experiments place when measuring properties of materials is always a fiddly but necessary additional job. In a simple case, when measurement sensors spatial orientation is not important, coordinates of sensor could be determined with several alternative ways like various triangulation methods, by measuring signal propagation time from reference signal sources etc. In more complex situations orientation of measurement sensor must be accounted. It is the case of sensors using polarized radiation or when properties of interest should be measured from certain direction only.

Coordinates of the least three points related to sensor must be given with high accuracy to determine sensors spatial orientation. Uncertainty of coordinates must be significantly smaller than distance between mentioned points. Therefore we needed like minimum four reference points and three points associated with sensor to build up 6 DOF positioning system. Commonly all those points are more or less complicated electronic devices which must work together. Main drawback of described system is spatial separation of its active components.

One possible solution is determining measurement sensors position and spatial orientation with photogrammetric method like described in authors earlier papers.

In that case passive coded targets would be reference points and pixels on the image sensor of digital camera, attached to sensor could be used as points associated with measurement sensor.

Solutions found earlier researching implementations of described system were not universal enough [1], [2], [3].

Solution proposed in present thesis using Bluetooth radio link for communications between measurement sensors and system's main unit, makes the 6DOF photogrammetric positioning system more flexible. Sensors with built-in Bluetooth radio are already in production. Using such off-shelf devices makes system even simpler allowing introduction of new sensors to system with programmatic means only.

2. 6DOF positioning system

Proposed 6DOF positioning system consists of a mobile device equipped with digital camera (e.g. cell phone) that is attached firmly to measurement sensor, coded targets printed on paper and software (see Fig.1.).

To eliminate the need of connecting wires and possible problems arising of corroded contacts Bluetooth link is used for communication between sensor and the cell phone. User must only guarantee that camera and sensor are securely attached.

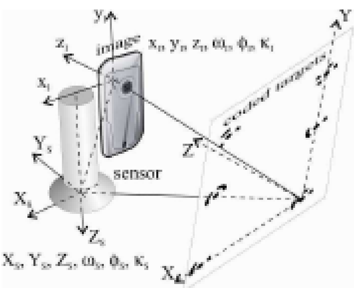

Fig.1. Main components of a 6 DOF positioning system

Coded targets in camera's field of view are photographed and corresponding sensors coordinates (X_S, Y_S, Z_S) and Euler angles ω_S, ϕ_S, κ_S for determining orientation in user defined coordinate system (X, Y, Z) are calculated in each measurement point. Measurement results are saved in camera's image file to assure that results and coordinates are in good correspondence and also to ease later processing of results.

Analysis of results is carried out with a photogrammetric software "Photomodeler Pro" running on an ordinary PC.

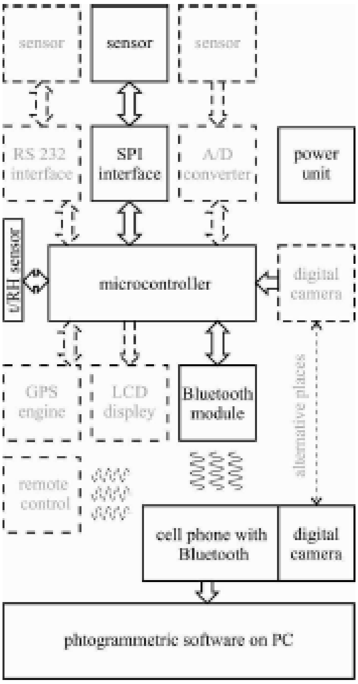

Fig.2. Block-diagram of Bluetooth photogrammetric positioning system

A cell phone with digital camera is used as system's central unit. Modern mobile phones have powerful processors, are equipped with Bluetooth radio and digital image sensors with resolutions up to 10 megapixels. Such cameras could be easily calibrated (to correct geometrical distortions on the digital image caused by optical and electrical parts of the camera) and used in short range photogrammetry [4]. Recent models of cell phones also have large enough memory devices to store images.

Majority of sensors still lack the ability to communicate via Bluetooth. Therefore a separate controller unit must be built to make use of such sensors. Controller must be universal enough to accommodate as much as possible existing (costly) sensors.

In order to accomplish above described tasks, a relatively simple yet versatile and powerful controller has been designed and built (see Fig. 2. and 3.).

Design was lead of concept that in minimum configuration circuit must guarantee some basic functionality only including communication with sensor and maintaining Bluetooth link with main unit.

Later improvements should include digital image sensor and GPS engine thus giving sensor station ability for stand-alone determining of position using above described method and operation as well. First prototype of controller uses of a Bluetooth module for radio link. This small OEM-module is built around Ezurio's product featuring relatively low power consumption and excellent sensitivity. Controller "sees" Bluetooth engine as a modem that could be controlled by means of a dedicated set of AT-commands. Communication speed is selectable yielding high baud rates up to 961 kbps.

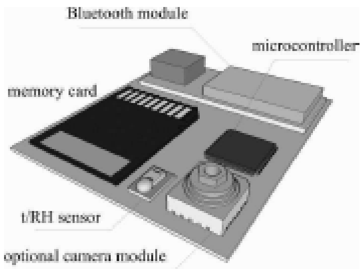

Fig.3. Prototype sensor unit with Bluetooth comm's link and humidity sensor

Controller has its own unique "network" address.

A small information screen displaying sensors current activities is included to the circuit. If not needed, it could be replaced by a LED indicator or omitted from the circuit.

The controller has one SPI-port and one standard RS232 port for interfacing to various sensors or measuring devices (see Fig. 2.).

In authors setup the SPI channel is used for connecting a RF - humidity sensor "Moist 200" for experiments like described in paper [1].

10 channels of PIC microcontroller's built-in analog to digital converter are available for sensors with analog output only. The converter has 10 bit resolution. One channel is used to monitor unit's power supply. Warning is sent to main unit in case battery needs replacement.

Since nearly every experiment uses atmospheric data like ambient temperature and possibly humidity, a simple temperature- and humidity sensor from Sensirion is included to circuit.

Since processor has the ability to reconfigure it's pins for digital IO, co-author of the paper interfaced the system to his portable gamma spectrometer - datalogger "Gammamapper". Since spatial orientation is not very important in environmental gamma radiation measurements, position fix from GPS engine is adjusted with photogrammetric method only if needed (if nature of found object requires more exact positioning). "Gammamapper" can cipher results on the fly and store them on a standard memory card. This instrument is described in greater detail in paper [2] (see Fig.4.).

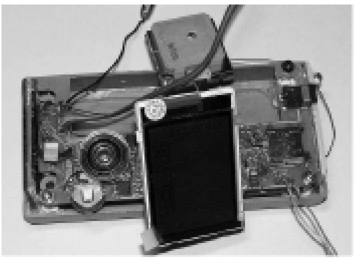

Fig.4. On the photo: new prototype of "Gammamapper" partly assembled

Possible extensions like image sensor and GPS engine are shown on Fig.2. with dashed lines. They are present in the circuit but are not yet implemented in first prototype version.

Measuring process is controlled and uplink to main unit is maintained by firmware running on a standard off-shelf microcontroller manufactured by Microchip. This microprocessor was chosen due to its low power consumption and rich set of on-chip peripherals.

Firmware is written entirely in assembly language to improve speed of operations.

Control code also handles storing measurement data to onboard flash memory if the device is set for long time measurements when radio link to main unit is not accessible.

Control software running on main unit (cell phone in our prototype system) establishes connection with all sensors and configures them for the experiment. It is possible to start every measurement cycle by command from main unit but sensor could also be configured to initiate measuring at predetermined time and for determined period or number of cycles. Delays between each cycle and various other parameters of sensor could also be set via network.

A Bluetooth remote control is incorporated to the system to improve ergonomics and convenience of measurements.

It should be noted that another simple mean of 3D positioning exists.

A large variety of cell phone models are available. Many have built-in sensors (eg. thermometer, sound level meter, etc). Usually spatial orientation of those sensors is not important so limiting to 3D positioning only is justified.

Using phone's build in sensor is straightforward. One should only take a snapshot of each measurement point taking care that there are enough coded targets in view. Binding image files to sensors readings could be done in numerous ways, even with pencil and piece of paper.

Photogrammetric software can generate a 3D map of sensors readings using captured image files.

Taking a snapshot of measurement place is a good idea even in case no coded targets are available.

For example, if a necessity arises to measure noise pollution with a Nokia 5140 cell phone, one should only take a photo and write down noise level. Photogrammetric methods allow determining sensors coordinates analyzing (natural) objects on the scene. Accuracy of coordinates is not so brilliant in this case. Coordinates determined by centres of coded targets could be automatically calculated with accuracy of 0.1 pixels whereas accuracy of marks made by user can not be determined with better accuracy than 1..2 pixels.

3. First results

Positioning system was tested on test field that was made of different kind of objects with well-known geometry. It helped conducting accurate direct measurements of sensor locations and spatial orientations. Coordinate system was marked with corded targets. Under the test were two cell phones – Sony Ericsson P900 with simple 0,3 megapixel VGA camera and Nokia 6288 with more advanced 2 megapixel camera.

Important parameters for photogrammetric positioning of these cell phones and their cameras were as follows:

Sony Ericsson P900 – FOV_H (field of view in horizontal direction) 42,5°, FL_{35mm} 44,6mm (focal length 35mm equivalent), picture dimensions 640×480 pixels, exif version 2.1, Bluetooth.

Nokia 6288 - FOV_H 51,9°, FL_{35mm} 35,5mm, 1600×1200 pixels, Exif V2.0, Bluetooth.

With both calibrated cameras (calibration made by standard automated routines included in software Photomodeler Pro on pictures taken from the calibration grid) was made 6DOF positioning of the camera and measuring sensor and compared with directly measured coordinates by vernier calliper and laser distance meter.

For Sony Ericsson P900 the RMS residual for different measuring points was between 0,6 .. 1,2 pixels. It means that for a 2 m dimensional test field accuracy is about 2 to 4 mm. Orientation uncertainty was better than 0,07 degrees.

For Nokia 6288 the RMS residual was in interval 0,35 to 1 pixel (0,5 to 1,5 mm for 2 m test field) and orientation uncertainty < 0,04°.

Direct orientation measurements were not made due to lack of necessary equipment. The positioning accuracy is not very good (5 to 10 times less than theoretically possible).

Numerous reasons could explain lower than expected accuracy. Firstly, the quality of marking coded targets snapshots was not best possible due to poor lighting conditions. Secondly cell phones software uses proprietary and unknown algorithms for compressing pictures which introduces additional marking errors. Optical system of tested phones was not very good etc.

Special software for the cell phone does not yet exist in time of writing this paper. Data was transferred using cell phone's own software. It means that measurement automation is not yet very good and real measurement positioning for practical purposes is difficult. In near future we plan to use the "Android" cell phone platform. It is an open source operating system for mobile devices with well developed support for peripheral devices. First cell phones running "Android" should be available in this year already.

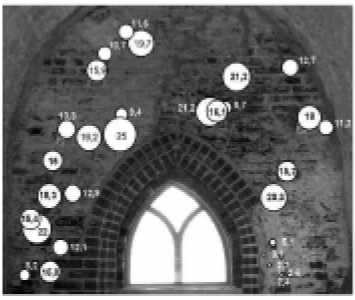

Fig.5. Moisture content in different points of the wall in percentages measured with microwave aquameter "Moist 200"

For an application example photogrammetrically positioned results of moisture content measurements of the wall in St John's Lutheran Church in Tartu (Tartu Jaani Kirik in Estonian) are on the figure 5.

4. Conclusions

First experiments demonstrated the possibility of using cell phones with digital camera for photogrammetric positioning of the measuring sensors. Accuracy of results with even a simple 0,3 megapixel cameras is acceptable for many applications. In order to achieve better positioning accuracy one must use a camera with better resolution. Using Bluetooth radio link for communication between sensor and main unit makes possible setting up different applications for mapping measurement results without any connecting cables. Rapid development in sensors architecture makes available big number of sensors with built-in Bluetooth interface. Using that type of sensors makes possible limiting to using only a cell phone, sensor and special software for 6DOF positioning of the sensors. For traditional sensor types a controller described in this paper could be used.

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APPENDIX 7
Article V

V. Sinivee. YСТРОЙСТВО ДЛЯ ДИСТАНЦИОННОГО YПРАВЛЕНИЯ ЭКСПЕРИМЕНТОМ ЧЕРЕЗ ЭЛЕКТРОННУЮ ПОЧТУ. *ПРИБОРЫ И ТЕХНИКА ЭКСПЕРИМЕНТА*, 2007, № 4, с. 1–5.

ПРИБОРЫ И ТЕХНИКА ЭКСПЕРИМЕНТА, 2007, № 4, с. 1–5

ПРИМЕНЕНИЕ ВЫЧИСЛИТЕЛЬНОЙ ТЕХНИКИ В ЭКСПЕРИМЕНТЕ

УДК @@@

УСТРОЙСТВО ДЛЯ ДИСТАНЦИОННОГО УПРАВЛЕНИЯ ЭКСПЕРИМЕНТОМ ЧЕРЕЗ ЭЛЕКТРОННУЮ ПОЧТУ

© 2007 г. V. Sinivee

Department of Physics, Tallinn University of Technology
Estonia, 19086, Tallinn, Ehitajate tee, 5
E-mail: felch@staff.ttu.ee

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Описаны приставка к персональному компьютеру и управляющая программа, позволяющие по электронной почте отслеживать состояние восьми логических входов, управлять восемью логическими и двумя аналоговыми выходами, а также перепрограммировать таймер. Сообщения об изменении состояний входов могут отсылаться автоматически или по запросу. Выполняются только команды, посланные с электронных адресов, указанных пользователем. Заголовок электронного письма можно использовать как пароль.

PACS:

Часто сбор экспериментальных данных или непосредственное проведение конкретного опыта может занимать много времени. Например, получение спектра с хорошей разрешающей способностью от объекта с низкой активностью может занимать часы, а иногда и значительно больше времени. В случае отключения электрической сети было бы неплохо уведомить экспериментатора о том, что эксперимент продолжается с помощью аварийного источника питания. Поскольку некоторые чувствительные и дорогостоящие приборы могут при длительном отсутствии питания выйти из строя, полезно иметь также информацию о состоянии (вспомогательного) источника питания, а также получать предупреждение о скором истощении его заряда.

Ясно, что в случае экспериментов, проводимых непрерывно в течение дней, экспериментатор, как правило, не может находиться все время у аппаратуры. В этом случае желательно иметь возможность изменения важнейших параметров процесса дистанционно (например, из дома).

КОММУНИКАЦИОННЫЙ КАНАЛ И ПРОГРАММА

Одним из наиболее распространенных каналов связи является интернет – кабельная или работающая по радиоканалу сеть. В большинстве общественных мест имеются также Wi-Fi-услуги.

Вторым, порой более распространенным каналом является GSM-сеть. Используя обе сети, мы получаем канал связи с очень большим радиусом действия. Он позволяет следить за экспериментом, проводимым в лаборатории (а также за другими устройствами, нуждающимися в дистанционном управлении), и изменять его ход практически отовсюду.

Описываемое ниже устройство отслеживает состояние до 8 входов, подсоединенных, например, к лабораторным приборам, источникам тока и т.д. Состояние выходов устройства можно также изменять дистанционно. В случае необходимости в схему можно добавить до двух аналоговых выходов, собранных, например, на микросхеме MAX518 (аппаратно можно больше, но программа поддерживает пока только два выхода).

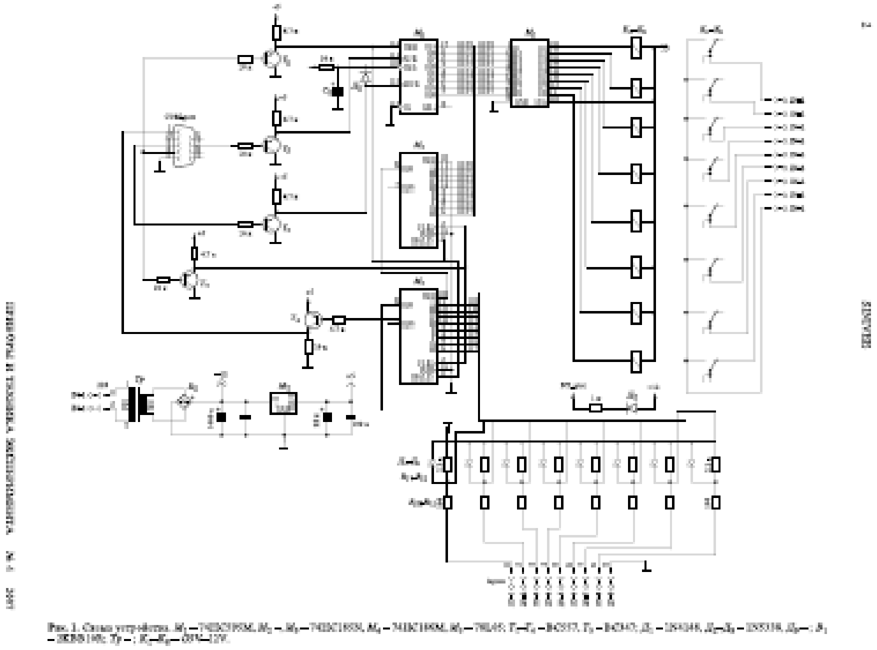
Благодаря относительно простой схеме, воспроизведение устройства не представляет трудностей.

Описываемое коммуникационное устройство соединяется через обычный COM-порт настольным компьютером. При отсутствии порта можно применять преобразователи USB–COM.

Управляющая программа в компьютере непрерывно следит за входами устройства и его состоянием. Все изменения учитываются, и при необходимости посылается сообщение об аварии.

Выходы устройства можно запрограммировать на переключение при помощи таймера управляющей программы (до 10 событий в день); ими можно управлять вручную или при помощи команд, посылаемых по электронной почте.

Для посылки команд можно создать отдельный почтовый адрес, но подходит и уже имеющийся почтовый адрес пользователя. Программа регистрирует все полученные приказы. Чтобы не захламлять почтовый ящик, после выполнения команд содержащие их электронные письма стираются. Посторонние электронные сообщения программа не трогает, выполняются только при-



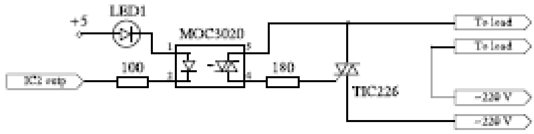


Рис. 2. Включение нагрузки симисторами.

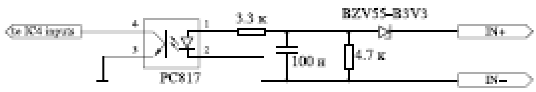


Рис. 3. Входы с оптической развязкой.

казы, посланные с электронных адресов, указанных пользователем. Заглавие электронного письма можно использовать как пароль.

СХЕМА

Основным компонентом выходной части устройства является 8-разрядный регистр сдвига M_1 типа SIPO (см. рис. 1). Данные, поступающие со связного порта на вывод 14 микросхемы, записываются в регистр положительными фронтами тактовых импульсов, поступающих на вывод 11 схемы. Информация передается на выход микросхемы при действии стробирующего импульса на выводе 12. Элементы R_8, C_5 и $Д_1$ сбрасывают регистр в исходное состояние при включении питания.

Поступающие от COM-порта сигналы преобразуются на уровни TTL буферами/инверторами на транзисторах T_1–T_4. При желании можно применить и специальную интерфейсную микросхему MAX232.

Микросхема M_2 является мощным буфером для подключения к устройству нагрузки повышенной мощностью (реле, сигнальных ламп и т.д.). Для визуальной индикации состояния выходов в схему можно включить светодиоды, как это показано на рис. 1 (показан один светодиод $Д_8$).

Мощной нагрузкой получающей питание от сети, целесообразно управлять с помощью не реле, а симистора, используя для гальванической развязки оптроны (см. рис. 2).

Микросхема M_3 – 8-разрядный регистр сдвига типа PISO – используется для контроля работы схемы. По команде управления M_3 считывает реальное состояние выходов. Если оно отличается от требуемого, пользователю посылается сообщение об ошибке. При необходимости контроль можно выключить и использовать освободившиеся выводы в качестве дополнительных входов, или вообще исключить микросхему M_3.

Регистр M_4 работает аналогично M_3. Программа непрерывно опрашивает входы и записывает изменения состояний в журнал (если разрешено). Пользователь получает состояние входов по соответствующему запросу (по электронной почте) или автоматически, если такой режим включен ("send mail-message on change" в меню конфигурации входов). Стабилитроны $Д_2$–$Д_9$ и резисторы R_{25}–R_{32} защищают микросхему от перегрузки. Резисторы R_{17}–R_{24} поддерживают свободные входы схемы на нулевом уровне сигнала.

При необходимости входы можно изолировать от схемы устройства при помощи оптронов (см. рис. 3). Уровни срабатывания оптоизоляторов определяются напряжением стабилизации стабилитронов. В конкретном примере напряжение до 3.3 В на входе считается "нулевым" уровнем.

Устройство можно питать от обычного стабилизированного источника питания (см. рис. 1), однако питание +5 В можно получить, например, из PS2- или USB-разъемов управляющего компьютера.

Существуют различные варианты монтажа устройства. Автор применил стандартный корпус для DIN-шины размером 3M и стандартную макетную плату.

ЯЗЫК КОМАНД

Командный язык устройства пока невелик. Команды могут иметь три формы:

<Command>;

<load_number_action>;

<load_number_action_time_date>.

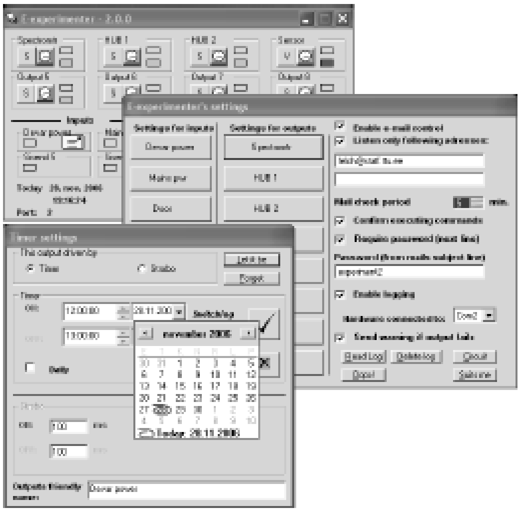


Рис. 4. Окна программы.

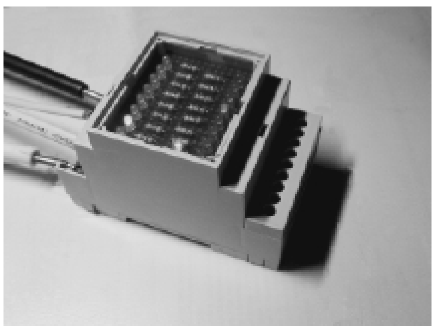


Рис. 5. Внешний вид авторского варианта устройства.

Корректная команда начинается символом "<" и заканчивается знаком ">". Остальные тексты игнорируются. Все команды записываются в журнал.

Устройство подчиняется следующим командам <Command>:

LOG – посылает содержимоежурнала;

STATUS – оповещает о состоянии на настоящий момент входов и выходов;

TIMES – посылает запрограммированные таймером времена, а также для контроля системное время управляющего компьютера.

Пример: команда <LOAD_1_ON_11:22:00_14.12.2006> активирует (включает) первый выход 14. декабря 2006 г. в 11.22. Команда <LOAD_1_ON_NOW> активирует первый выход немедленно.

ПОЛЬЗОВАТЕЛЬСКИЙ ИНТЕРФЕЙС

В окне программы отображаются клавиши включения-выключения выходов и кнопки для передачи управления выходами на таймер, отображаются также текущие состояния входов (см. рис. 4).

Красная "аварийная кнопка" выключает все выходы и отменяет (но не стирает) программы таймера. Клавиша "settings" открывает конфигурационный диалог, посредством которого можно изменять различные элементы программы (присваивание входами и выходами имен, установку параметров электронной почты, отображение принципиальной схемы устройства и т.д.).

Исходный текст программы (на языке Visual Basic 6.0), принципиальная схема и описание языка команд находится в одном архивном файле: eexperimenter2.zip. Файл можно "скачать" с адреса http://parsek.yf.ttu.ee/~felc/eexperimenter2.zip. Опубликованный код (или его части) доступен всем желающим по правилам GNU-лицензии.

APPENDIX 8
Article VI

V. Sinivee. Simple yet efficient NMEA sentence generator for testing GPS reception firmware and hardware.

Simple yet efficient NMEA sentence generator for testing GPS reception firmware and hardware.

V. Sinivee MSc
Department of Physics
Tallinn University of Technology
Ehitajate tee 5
19086,Tallinn, Estonia

Keywords: GPS, binding data to geographic coordinates, positioning, spectrometer, NMEA, SIRF-Star, test pattern, test sequences generator, testing, DUT.

***Abstract*- A simple device for generating NMEA sequences for testing embedded GPS reception firmware and hardware is described. Device can work in standalone mode and also in conjunction with control software. Configuration program can be used to generate test strings without tester hardware as well.**

I. Introduction

It is often desireable to bind measured (field-) data with exact time and coordinates, especially in handheld mobile enviromental instruments. Geographic data is usually obtained from a GPS-receiver. Modern GPS engines have lots of attractive features: they are small and economic, output data could be read easily. Due to minute power consumption use of such receiver in battery powered apparatus is justified.

GPS is very useful mean of positioning in a simple case when measurement sensors spatial orientation is not important.

Cases exist where 3 coordinates are not enough to guarantee needed accuracy and repeatability of measurements. A good example is measuring moisture contents of various materials. Since the 30 cm range moisture sensor of „Moist 200" instrument uses polarized microwave radiation, it is essential to determine probe's spatial orientation. If the tested sample/object has a fibrous structure, results depend much of sensor's rotation angle around its longitudinal axes. Described effect is clearly visible when measuring, for example, moisture of paper. For such cases a more precise 6-DOF positioning system like described in [6] could be used.

Author of present thesis used GPS engine to bind spectral data from an experimental portable gamma spectrometer-datalogger „GammaMapper" with geographic coordinates. In this device coordinates from the GPS receiver are stored together with every preset amount of gamma events thus allowing the experimenter build radiation maps of his/her everyday environment [3].

Data from a standard GPS-receiver is output in form of various so-called NMEA sentences. In NMEA mode data is presented as a stream of ASCII characters. A „SIRF-Star" binary format also exists.

Receiver's output stream combines lot of information divided into different protocols. Device description is usually also transmitted on engine power-up.

On start-up or in poor visibility acquired coordinates could be not valid. For example in protocol $GPRMC (Recommended minimum specific GPS/Transit data) a special character – letter 'V' or 'A' indicates fitness of data. More information about protocols used in GPS data transactions and their meanings could be obtained from [1,5,8].

Part of designing process of state-of-art instruments with embedded GPS engine envolves writing routines for decoding receivers output stream. For testing those routines one must have some kind of test data source. Unfortunately GPS data is usually not available indoors.

Another problem is simulating validity of data and erroneous stream reception. Good firmware must be able to handle errors ocurred due to poor signal level, problems in link between GPS engine and main processor of instrument under test (protocol and hardware errors) etc. Using data output by standard GPS-receiver even with many satelites in view does not offer means for testing all mentioned situations.

Numerous excellent programs have been written for decoding NMEA and binary messages of GPS receivers.

There are not so many reverse converters i.e. programs simulating a GPS receiver. „GPSSIMUL" [9] is a good freeware (30-day trial version) NMEA sentence simulator that could prove to be practical in many cases. Unfortunately it (like multiple other programs author could find) simulates only correct and only NMEA sentences.

In some situations a stand-alone configurable (low-power) test generator with a wide range of supply voltage and possibility to simulate errors is more preferrable.

Present thesis describes a prototype GPS data simulator designed and built in Department of Physics of Tallinn University of Technology. First version of the device was limited to generating only one NMEA message and enabled simulation of communication errors (see fig.4.). Later versions were developed to a more universal device with control via a GUI running on an ordinary PC.

II. Simulator Hardware

First solution of described problem was writing a simple firmware for a low-cost and readily available microcontroller generating only needed NMEA sentences (see fig.1.).

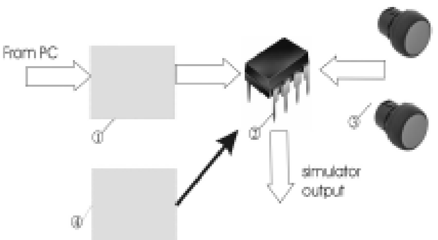


Fig. 1. GPS simulator's block-diagram. 1 –optional USB or RS232 interface, 2 – microcontroller, 3- control buttons, 4 – optional adjustable power supply.

Core of the circuit is a small microcontroller (2). Two modifications of the output data stream were made available via jumper/pushbutton (3) settings: simulation of a „position not valid“ flag and erroneous sentence (one that was prematurely terminated).

Optionally an adjustable power supply (4) could be added to circuit for using it with processors with a non 5V supply voltage.

For configuration the board must be connected to a PC via USB or serial interface (1).

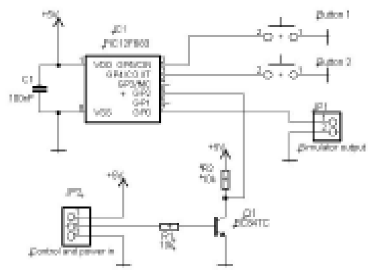


Fig. 2. Test sequences generator's electrical circuit.

Prototype of the GPS tester was built on Microchip's popular PIC series processor [4] due to it's availability, low power consumption, wide range of supply voltage and also due to author's experience in writing software for them.

Heart of the simulator is IC1 (see fig.2.). Microcontroller generates all needed test protocols. Data is output from a bit-banged serial port [7] via pin GP0.

Above mentioned jumpers were replaced in present version with buttons. External pull-up resistors were not used since PIC micro controller can be configured to use internal pull-ups.

Capacitor C1 is a standard mean of suppressing noise generated more or less in all digital circuits.

Transistor Q1 together with R1 and R2 form a level shifter circuit to connect the device with a PC via standard serial port. If the device will be used in standalone mode only, mentioned components except resistor R2 may be omitted.

Since PIC12F683 used in described circuit lacks internal USART, reception of control commands is realized via a "bit-bang" software serial port [7] working at a fixed baud rate of 4800 bd.

A standard USB port is a very convenient and handy mean for powering the device and communicating with PC since serial ports are nearly extinct. One could use an off-shelf USB to RS232 converter together with a MAX232 level shifter IC or build one on a special chip – FT232RL manufactured by FTDIchip [10].

Powering the PIC microcontroller form a separate adjustable supply allows using the tester circuit for debugging hardware with supply voltage in range of 2,7...5,5V. A standard LM317 voltage regulator (not shown on circuit) could be used for this purpose.

Full digital control of devices features might include adjusting supply voltage. A MAX518 digital to analog converter is suitable for this purpose since the PIC microcontroller operates in nanowatt power mode.

The D/A chip could get it's instructions form PIC microcontrollers outputs dedicated normally to switches (since control commands and button press events usually do not occur simultaneously) or a controller with different I/O count could be used.

Author of present thesis implemented I^2C control of the D-to-A chip using mentioned switch outputs (GP0 and GP1 on figure 2).

PIC-microcontroller's internal brown-out control's voltage threshold should be set below minimum operational voltage in that case (2,0V is recomended).

Figure 4 showing the control program does not yet reveal possibility of supply voltage control of the board.

III. SIMULATOR FIRMWARE

Main work mode of the GPS simulator described in present thesis is a standalone mode without control from PC. At first start there will be no saved test sequences in device's EEPROMmemory. Therefore the device defaults to emulating only a correct "$GPRMC" sentence every second.

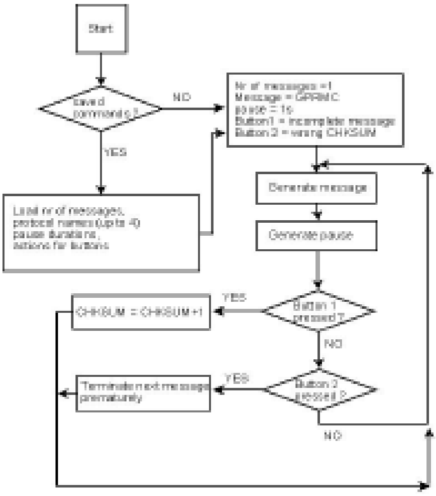


Fig. 3. Test sequences generator's work flow.

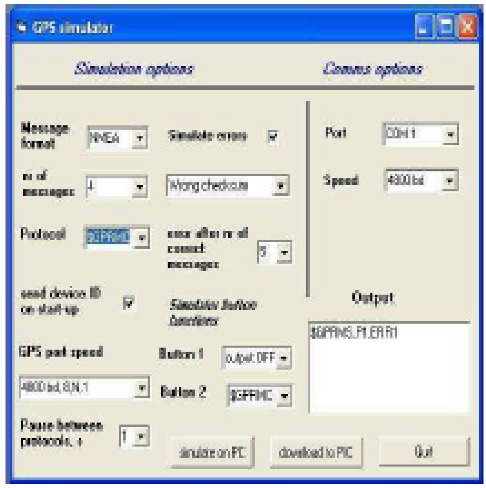


Fig. 4. Main screen of control utility.

Pressing button 1 sets flag "position not fixed" in output message and pressing button 2 terminates next message prematurely. Normal messages will be generated if both buttons are released (see fig.3.).

High-speed operation and compact code of the device is achieved by using assembly programming language.

IV. CONTROL GUI

In order to make described device more universal, major changes were made to it's firmware and a small control program was written.

Figure.3 shows utility's working screen. This program uses Windows platform and allows sending different NMEA protocols to the simulator micro controller. One can select number of simultaneously generated different sentences. Also a device ID could be sent on start-up. Since it differs from ordinary data stream, it could cause crashing of firmware of the device under test. Device ID could be of arbitrary length and contents.

Pause between emitting different protocols is also configurable.

Baudrate of the GPS-engine simulated is selectable between 4800 bd up to 115200 bd. Other parameters of communication port could be configured as well.

Control GUI lets user define different actions undertaken on button press event on the simulator board. Actions could be selected form a drop-down list. Both buttons could be configured separately.

Selections are:

- sending selected standard protocol,
- switching output off or on again,
- simulating error in communication,
- changing port speed (simulation of error case)
- sending a device ID etc.

It must be noted that user composed messages or device ID-s could be sent to DUT form the "Output" text box. If there is a message in text box, corresponding option appears to all relevant drop-down selection lists.

Freely composable messages make the device more universal not limiting it's use to the field of GPS systems only.

Comm's options menu controls connecting the simulator board to PC. Simulators own input baud rate is fixed to 4800 bd due to lack of resources for autobauding in used microprocessor.

Button "download to PIC" sends configuration data to the simulator board where it is saved to controllers on-chip EEPROM memory. Settings are applied immediately for the next message generated.

For users having no resources to build described simulator board, option of generating test strings straight from PC's own comm port was added to the GUI code.

V. Conclusion

Described in present thesis simple GPS signals simulator proved to be practical and useful. It has already saved author hours of debugging time in writing firmware for his portable spectrometer, the "GammaMapper" [3]. This was especially true while debugging the device described in [2].

Due to very compact hardware the device could be useful to other programmers working in field of instruments making use of embedded GPS engines.

In order to improve precision of timing of output test string a crystal resonator could be added to the circuit.

Author plans to write a newt firmware version which supports SIRF binary format messages as well.

Custom messages typed into the output box enables using the device as a universal test pattern generator not limiting to GPS applications only.

Parameters of described GPS-simulator's board are as follows:

- power consumption: 0,8 mA@5V;
- power supply range: 2,7...5,5V;
- output port speed: 4800...115200 bd;
- output format: NMEA;
- standard NMEA sentences simulated (in present firmware version): $GPGGA, $GPRMC, $GPGLL, $GPGRT, $GPRMB, $GPZDA;
- option of custom messages;
- option of simulating errors in output stream;
- configurable via control program running on an ordinary PC.

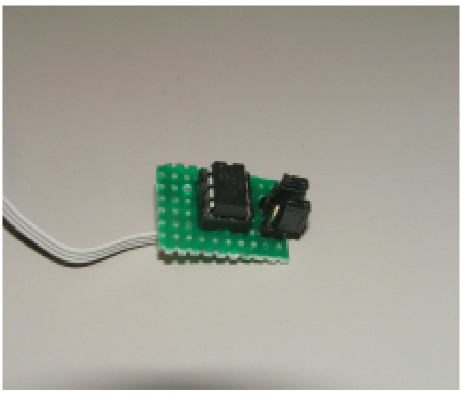


Fig. 5. First prototype of the simulator board.

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