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"QUANTOCHRON" - A MULTICHANNEL TIME-TO-CODE CONVERTER

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ABSTRACT. *A new type of the "time-code" converter "QUANTOCHRON" alows us to measure the time moments of registering photons through a photodetector with a time resolution up to 20 ns. The impulses to be registered can arrive to "QUANTOCHRON" by 8 or 18 independent parallel channels, depending on the version, which makes it possible to register information in* 2^8 *or* 2^{16} *physical channels, respectively. The accuracy of defining the time intervals between the registered photons is about 40 ns; the same measuring accuracy of the current time counts when the signals of the hour's service are used. The dead time of the converters is 60 ns. The design of "QUANTO-CHRON" allows us to increase the time resolution and the number of channels, if necessary.*

Описан новый тип преобразователя "время-код" - "КВАНТОХРОН", позволяющий измерять моменты времени регистрации квантов фотоприемником с временным разрешением до 20 нс. Регистрируемые импульсы могут поступать в "КВАНТОХРОН" по 8-ми или 16-ти независимым параллельным каналам, в зависимости от его модификации, что позволяет регистрировать информацию по 2^8 *или* 2^{16} *физическим каналам, соответственно. Точность определения интервалов времени между регистрируемыми квантами составляет величину порядка 40 нс; такая же точность измерения текущих отсчетов времени при использовании сигналов службы времени. Мертвое время преобразователей равно 60 нс. Принцип построения "КВАНТОХРОНА" позволяет при необходимости увеличить временное разрешение и расширить количество каналов регистрации. Аппаратура выполнена в стандарте КАМАК.*

An experiment is being carried out at the Special Astrophysical Observatory of Russian Academy of Sciences(SAO RAS) to search for "black holes" of stellar masses, which, according to theory (Shvartsman, 1971), have a wide range (a few minutes to a few microseconds) of radiation variability resulting from matter being accretted. To support this investigation a mathematical method of y_2-functions was developed by Schvartsman in 1972. This is a method of searching for the radiation variability of faint objects on times much shorter than the mean interval between events registered (Shvartsman, 1971). For the same task a hardware/software facility was developed, which included:

- a photometer, working in photon counting mode;
- a time-to-code encoder capable of measuring time intervals between a pair of consecutive events, received by either of two input channels;
- data acquisition and reduction software to accept data flow into the computer's memory and its reduction on the basis of y_2-functions apparatus (Mansurov et al., 1977).

Observations made at the SAO 6-m optical telescope showed the correctness of the mathematical approach and necessitated its further development and instrumentation upgrading. On the theoretical side the variability function apparatus was suggested by Shvartsman. This could be applied to any conceivable time intervals. It included the d_2-functions method of searching for variability on times greater than the mean interval between events. On the hardware side the Strobed Real Time Indicator, later referred to as "QUANTOCHRON-2", was designed (Pimonov, 1979). It was intended to record the time moments of registration of events but not the intervals between them. The device had five input channels. This instrument greatly widened the observational boundaries of the experiment. Observations of strictly periodic objects became possible. Work in search of young pulsars in the NGC 4321 and NGC 4647 galaxies was carried out (Beskin et al., 1981). An investigation of the Crab nebulae pulsar was carried out, its main pulse having been profiled with a resolution of 6 microseconds (Beskin et al., 1983) and 3.3 microseconds (Shvartsman et al., 1988). An investigation of the sky fields around the expected location of the shortest-period pulsar PSR 1937+214 was carried out.

In recent years, apart from the "black holes" search, investigation of flare stars has taken a significant share of observation time (Shvartsman et al., 1987). For the further development of high temporal resolution methods applicable to investigations of astrophysical objects it was necessary to:

- reduce dead time between the registration of individual events (it affects the Poisson properties of the incident flux of photon events) and improve temporal resolution;
- develop a device that could register spatial data as well. This would allow the registration of events through many input channels or the taking of data from a coordinate-sensitive detector;
- provide greater flexibility for the instrument in terms of detectors used. In

order to meet these requirements we have designed a new instrument called "QUANTOCHRON 3/8". The "3" in the name stands for the 3rd generation in the development of our time-code encoders. This device makes it possible to register eight-bit binary numbers as well as the moments of photon events arrivals. Hence the digit "8" in the name.

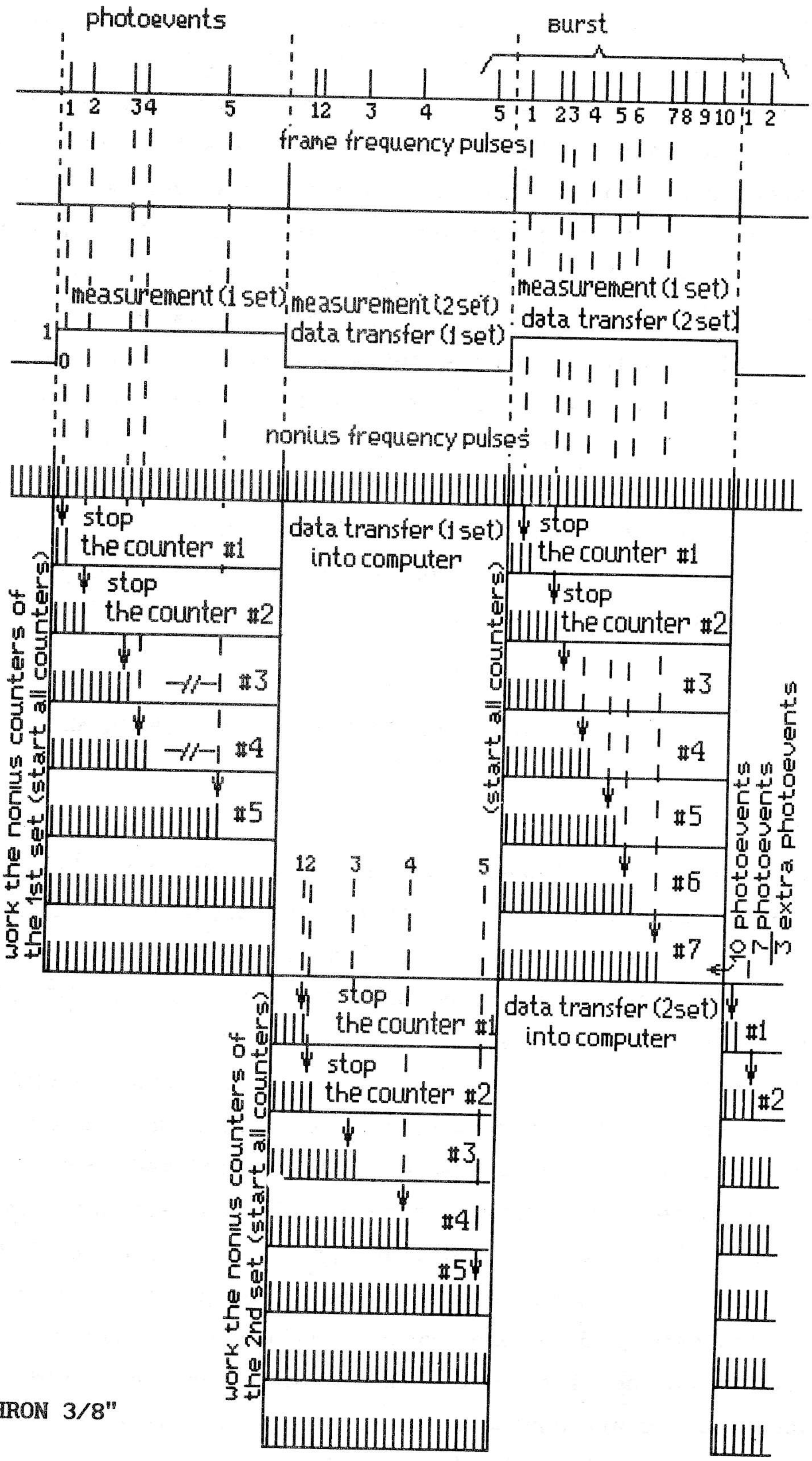

Fig. 1. Block diagram of the "QUANTOCHRON 3/8".

BLOCK DIAGRAM OF "QUANTOCHRON 3/8"

The device (Fig. 1) incorporates two identical sets of electronic components which are added to an ordinary counter. The main stages on the block diagram are:

1) A frame frequency counter to count time cycles or frames. The least significant

bit (LSB) of the counter switches the two sets between input/sample and output/hold modes of work and is used by data acquisition software to synchronize the device and computer;

2) Up to seven counters of high nonius frequency in a set which are activated simultaneously with each frame beginning and disabled successively at the moments of event arrivals. The signal to stop the next nonius counter is produced by the 1^{st} of the 8 decoders. The decoder is wired to a 4-bit binary counter of events;

3) Up to seven 8-bit storage registers in a set, each paired with a nonius counter. Registers serve for storing any information associated with the events. This information is latched in a register, simultaneously stopping the corresponding nonius counter. Although, in general, this additional information may be of any type and origin, i.e. colour, polarization, channel number, coordinates, etc., we will in future refer to these storage registers as coordinate registers. If this feature is not used we will refer to this as monochannel mode of work.

Such a set of counters and registers is sufficient for registering event arrival times and is associated with event information in a given frame frequency cycle. During the next cycle counters and registers should be read by computer. The exact same set of nonius counters and storage registers are then employed in order not to lose incoming data.

THE "QUANTOCHRON 3/8" DESCRIPTION AND ON-LINE PERFORMANCE

The "QUANTOCHRON 3/8" is designed to work in CAMAC standard. The device utilizes factory fabricated standard modules as well as specially designed ones. Physically, the device is a CAMAC crate with modules plugged in. In a CAMAC system modules are controlled by a crate controller which in its turn is controlled by a computer through an interface card and data link. We used an IBM PC/AT host computer and a 16-bit CAMAC interface card.

The device comprises two modules and some standard CAMAC counters to count nonius clock ticks. Of the two modules one is an interval counter control module, the other is an auxiliary, coordinate module. The control module counts cycles, controls nonius counters by issuing reset and stop signals, and synchronizes acquisition software.

A set of registers to store any information additional to photon-events (coordinates, channel numbers, etc.) has been created in separate coordinate module. Both the coordinate module and control module have connectors on their front panels through which they interface with each other and the world. Normally, interface links between modules are done with short pieces of coaxial cable. A diagram of the process of time measurement is shown in Fig.2.

The data acquisition program is synchronized with the device by the least significant bit (odd/even bit) of the cycle counter. The computer waits until the odd/even bit is toggled and then starts processing of corresponding set of counters and registers. Measurements and data transfers take place in counter-phase: whilst one set of circuitry takes measurements another one is in a frozen state and can be read by computer. Only those nonius counters which hold valid information are read. This is defined by the content of events counter. If it is empty the cycle under processing is dropped.

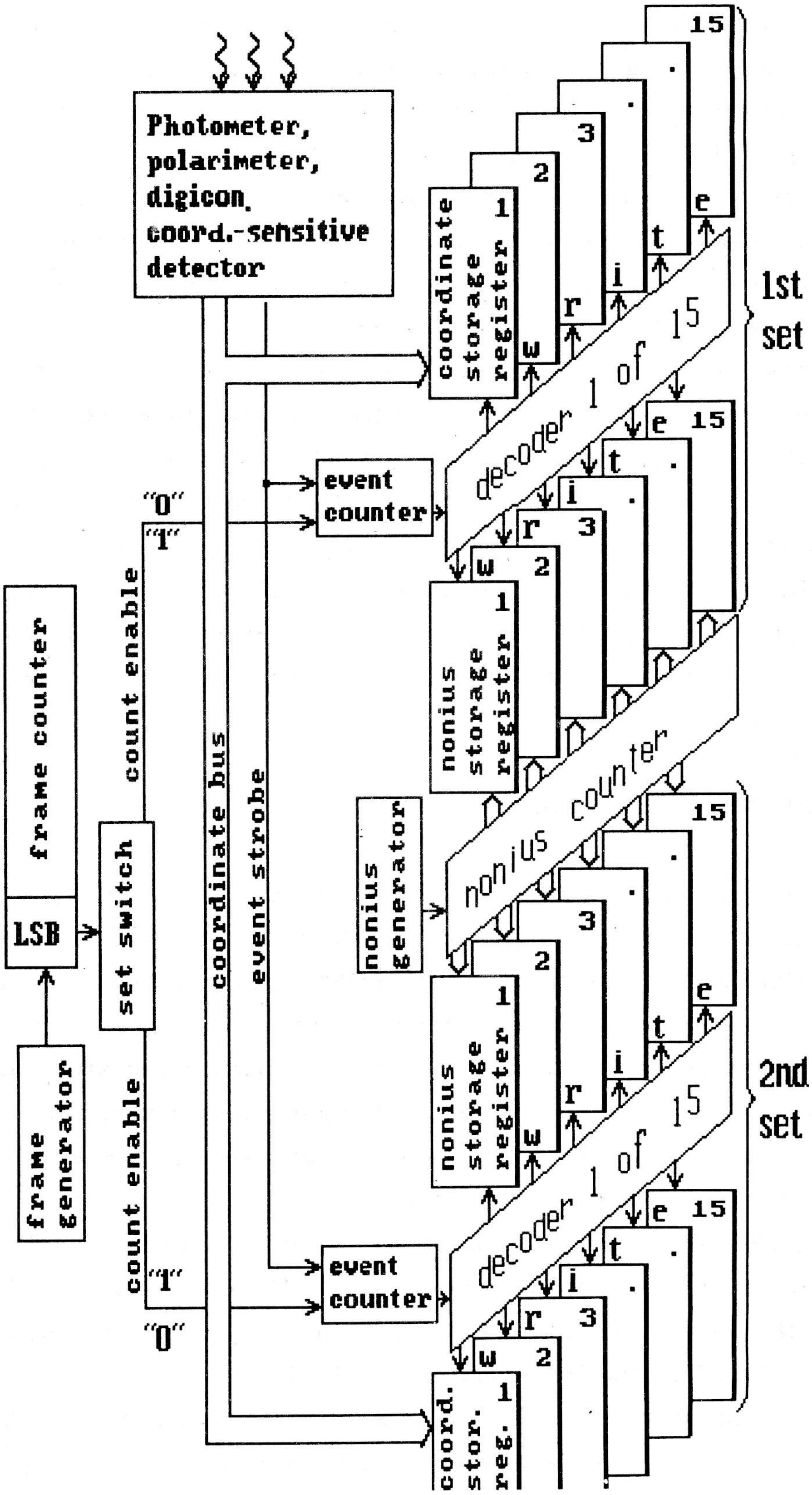

Fig. 2. Time diagram
of the "QUANTOCHRON 3/8".

While a nonius counter is being read the output enable line of a paired register is activated. As a result, both units simultaneously output their contents on CAMAC R-bus (read data bus). CAMAC bus operates in negative logic and permits wire-OR function on R-bus. Possible conflicts are ruled out by predefined bit distribution for any given experiment. The input coordinate bus is 8-bit wide, but it is easily possible to shift the boundary between the coordinate and interval parts of a 16-bit data word by letting the reduction software know the bits allocation. In all cases the coordinate part is allocated to the higher order bits of the data word, and interval part to the lower order bits.

The more bits we allocate for coordinates the less remain for the nonius counter. This necessitates the lowering of the nonius frequency thus limiting the time resolution. When only the 8-bit nonius counter is being used the resolution will make up about 400 nanoseconds (100 microsec/255).

For those cases where high time resolution as well as wider coordinate word length is desired, we have modified the device. The "QUANTOCHRON 3/16" has nonius counters and coordinate registers discriminately address mapped.

While observing with the "QUANTOCHRON 3/8" we regulate the input flux in such a way that the mean number of photon-events per cycle with high probability is less than 6. Taking the cycle period to be 100 microseconds we limit the flux to be registered to 15,000 - 20,000 events/sec. This is dictated by the fact that the "QUANTOCHRON 3/8" has only five counter/register pairs in each circuitry set.

THE "QUANTOCHRON 3/16" BLOCK DIAGRAM

For the next step in the development of the 3rd generation of our time-code converters we modified the design of "QUANTOCHRON 3/16". The basic difference between the "QUANTOCHRON 3/8" and the "QUANTOCHRON 3/16" is that the latter has only one nonius counter and two sets of fifteen storage registers to hold nonius counts. Each nonius storage register is paired with a coordinate register. Nonius as well as coordinate registers are 16-bit wide and are mapped separately in the CAMAC address area. Thus it becomes possible to acquire photon events from a two dimensional detector with an area of up to 256 by 256 pixels.

The "QUANTOCHRON 3/16" is able to transfer data under DMA control with a data transfer rate in monochannel mode of up to 150,000 words/sec. This means that approximately the same event input rate is allowed. When the coordinate module is utilized the intensity of input flux should be halved.

A block diagram of the "QUANTOCHRON 3/16" is shown in Fig. 3.

It is possible to extend the wordlength of the device up to 24 or 32 bits by employing a second coordinate module. It should be remembered though, that maximum event flux intensity will further decrease.

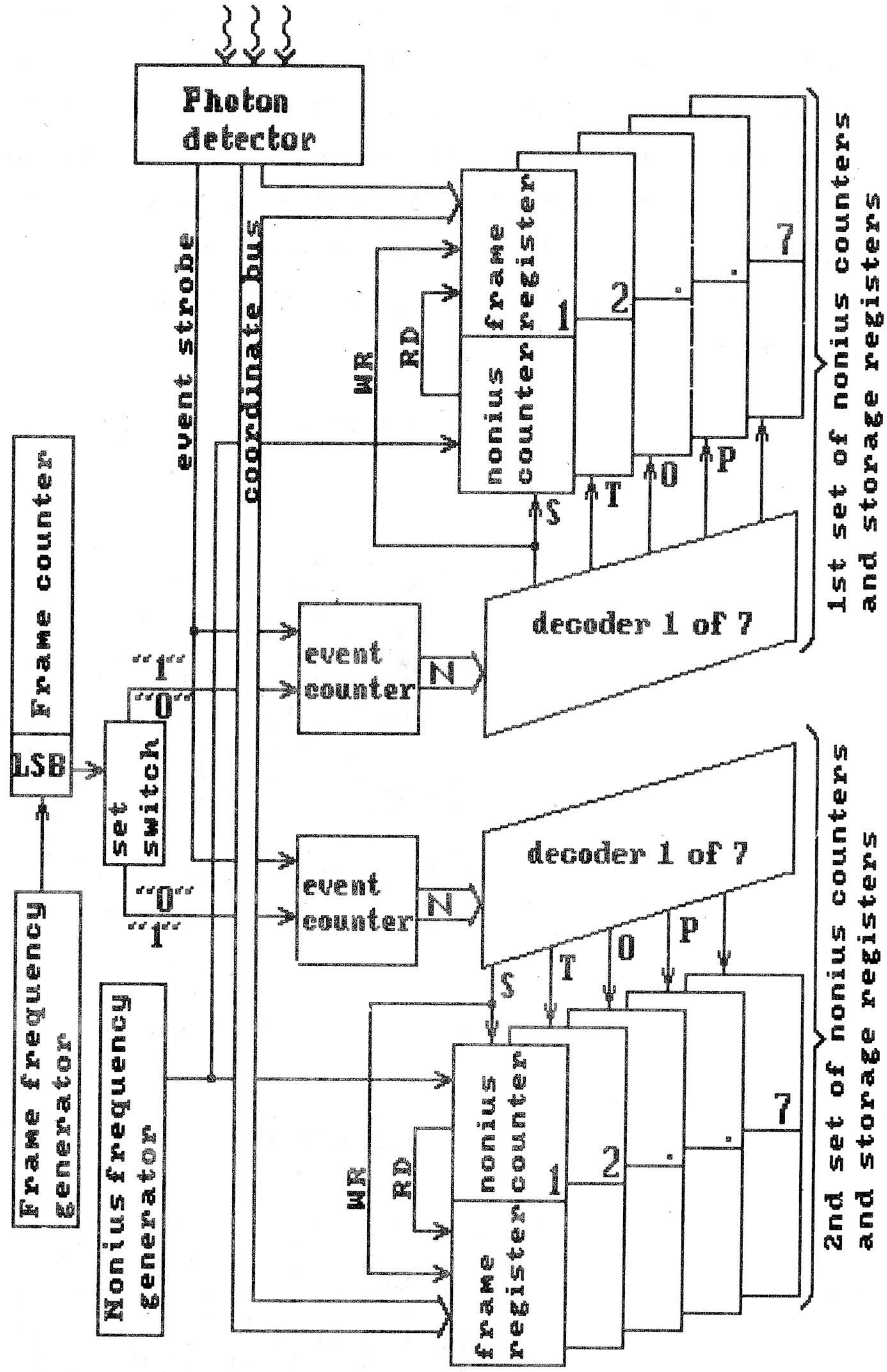

Fig.3. Block diagram of "QUANTOCHRON 3/16".

DATA FORMATS AND DATA ACQUISITION SOFTWARE

We have just described the basic software-accessed components of the "QUANTOCHRON 3": cycle counter, events register, and sets of nonius counters and storage registers, all of which have different bit sizes. We have hardwired all these components to optimize the performance of the instrument both in terms of maximum data

transfer rate and minimum unproductive waste of the host's memory.
The data format is shown in Fig. 4. At the beginning of a cycle the software reads data acquired during the preceding cycle. The status of the front panel switches and higher bits of the cycle counter are read once at the beginning of a large chunk of data. These are then followed by data registered during a frame (cycle). Frame data begin with the lower bits of both the cycle counter and of the events counter, packed together in one machine word. Then follow the words containing nonius counts and spatial information.

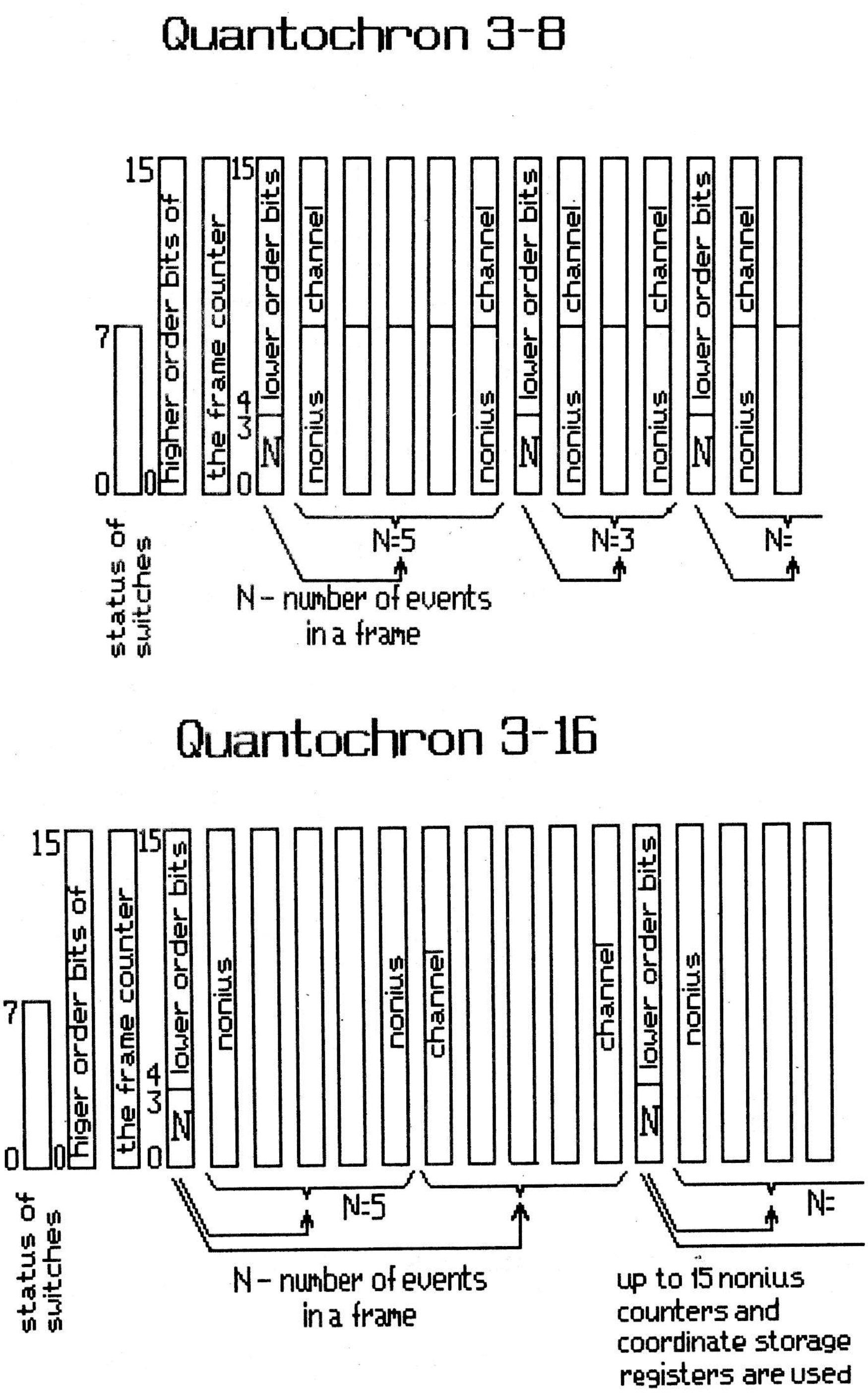

Fig.4. Data formats of the "QUANTOCHRON 3".

Their number is defined by the content of the events counter. If it is empty, no data concerning the corresponding frame will be transferred to the computer's memory. In the case of a flash of photons, the events counter may contain a value larger than the number of nonius counters available. It does not overwrap so the reduction software is able to distinguish such occurrences. Generally speaking, frame frequency should be matched beforehand with the expected flux intensity. Let us recall that in mono-channel mode the "QUANTOCHRON 3/16" operates at 10,000 Hz frame frequency, which is dropped to 5,000 Hz by the multichannel mode. Speaking in terms of incident flux it corresponds to 150,000 and 75,000 events/second, respectively.

Reduction software defines the frame and nonius frequencies by the value of the switch status word. The type of photon events detector, as well as details of a given experiment, may call forth specific reduction algorithms. For a photometer with a photo-multiplying tube as a detector we form arrays of time marks for each input channel. Frame and nonius values are converted to metric time units by the equation

$$t = T + N/ft + n/fn \quad ,$$

where T is start time synchronous with the observatory time service, ft, frame frequency, fn, nonius frequency, N, frame number, n, nonius count.

COMPARISON ANALYSIS OF TWO GENERATIONS OF TIME-TO-CODE CONVERTERS

Now we will scrutinize the three types of converters: "QUANTOCHRON 2" (designed by Pimonov, 1979), "QUANTOCHRON 3/8" and "QUANTOCHRON 3/16". The sketches shown in Fig. 5 will aid this.

Pimonov's device (Fig. 5a) has a time coding circuitry and a ring buffer of 4 registers. The ring buffer serves to smooth out bursts of photon events. But if a burst is too dense, data override is possible. What is worse, such occurrences can not be detected by hardware, and the statistics of fluxes being registered are liable to be incorrect.

Fig. 5b presents the "QUANTOCHRON 3/8" sketch. The device is composed of two sets of five nonius frequency counters working in counter-phase. The toggle between sample and hold states of a set is controlled by the LSB of the cycle counter. The latter counts pulses of standard carrier frequency provided by the observatory time service or the built-in frame frequency generator. Normally, it is 10 kHz.

Fig. 5c shows the sketch for "QUANTOCHRON 3/16". Its circuit layout peculiarities are touched upon in the previous chapter.

Both "QUANTOCHRON 3/8" and "QUANTOCHRON 3/16" are protected against excessive events being unnoticed. Events that come during a cycle are counted in 4-bit binary counter. At the raw data processing stage the software detects occurrences of cycles with excessive, unregistered event intervals. This is taken into account by statistical processing procedures.

If spatial data are not necessary, the coordinate module can be excluded from the device. Mode selection is done on the software level as well as on the hardware level by appropriately connecting input cables.

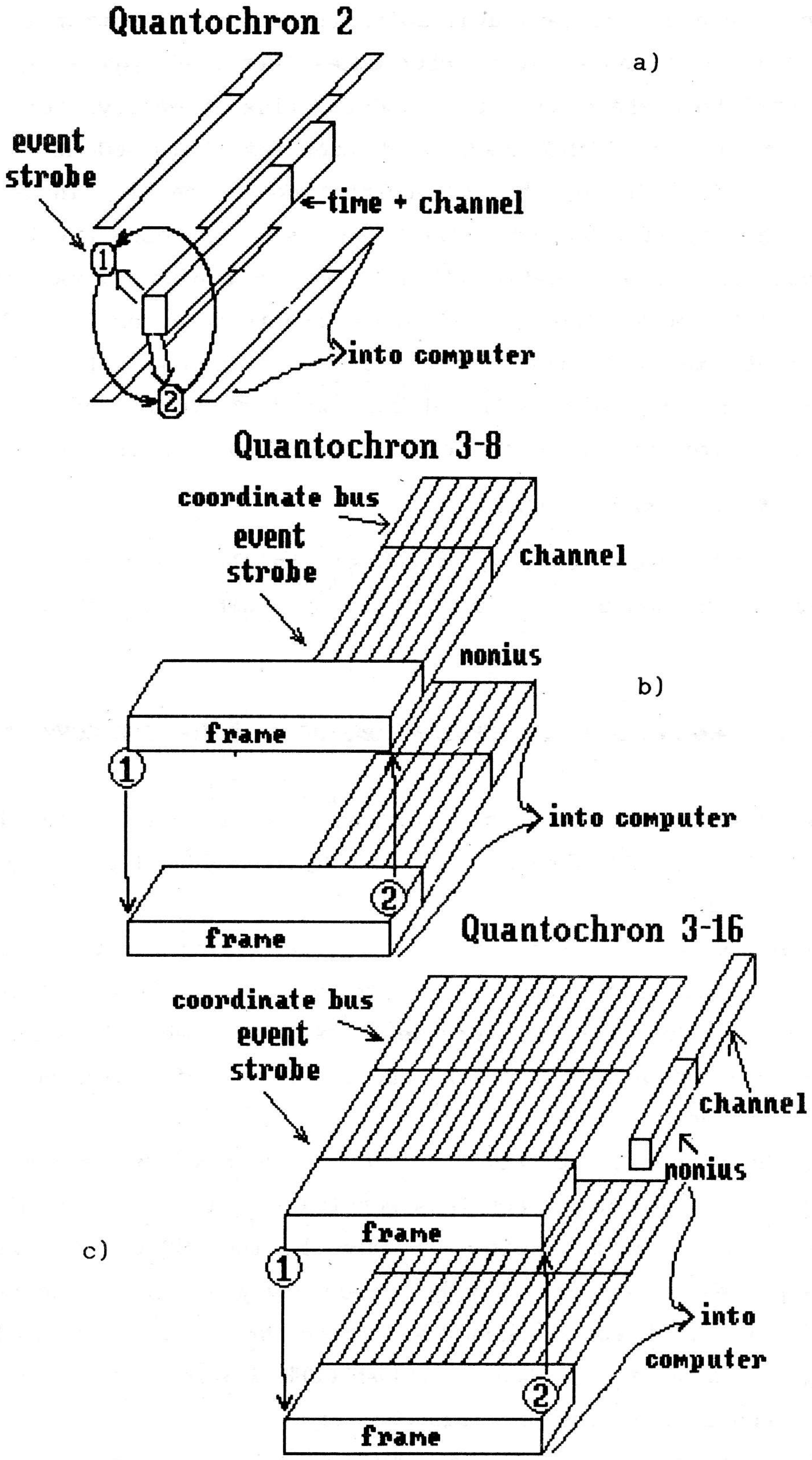

Fig.5. Comparison of different types of time encoders.

Prior to observation the device should be tested against the external high stability pulse generator or the built-in events simulator which has a wide range of fixed frequencies. The measurement accuracy of moments of pulse arrivals is analyzed. Histograms of measured intervals are then drawn up to study the deviation from the accurate pulse period. The built-in simulator circuit generates a series of high frequency pulses alternately distributed across channels (or coordinates) in a chessboard pattern. We use this simulator to test interval and coordinate circuitry functioning. Besides this, we investigate the statistical characteristics of the photometer exposed to an etalon source of photons. Photometer data are processed to search stochastic variability (Plokhotnichenko, 1983).

Fig. 6 shows typical histograms of measured intervals of standard frequencies. The time-to-code converters of "QUANTOCHRON 3" series allow an accuracy of 40 nanoseconds to be attained.

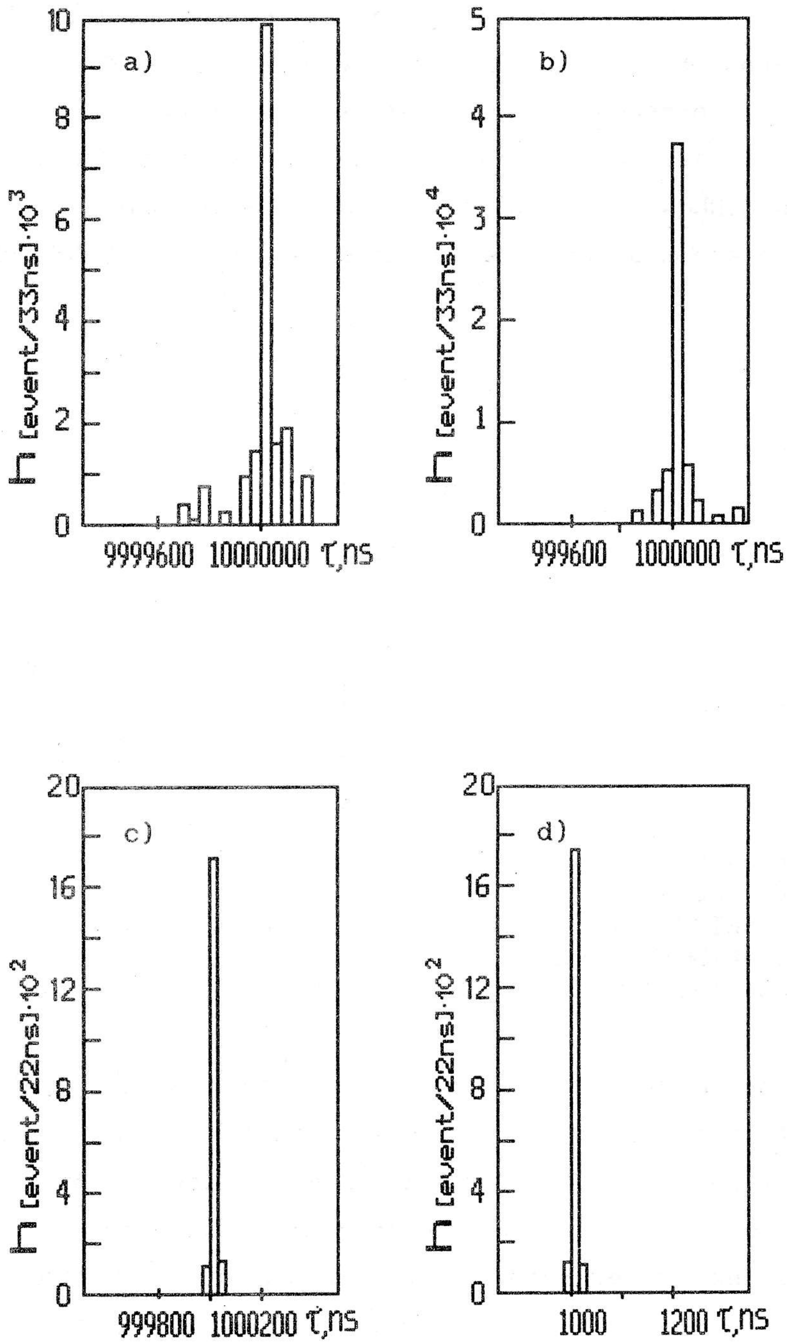

Fig.6. Histogram of dispersion of the standard frequency. a,b) test results of "QUANTOCHRON 2" at 1 kHz and 10 kHz; c,d) test results of "QUANTOCHRON 3-16" at 10 kHz and 1 MHz.

Test acquisition of coordinate validity shows hat at a coordinate rate of less than 10 MHz, the percentage of glitches is not more than 0.1% and is increased to 20% at 16 MHz. These failures are of code loss type.

The coaxial data link is tested with the help of ordinary engineering facilities such as the pulse generator, the oscilloscope and the pulse counter. The test aims to check for pulse reflection or other distortions over a range of frequencies. The photometer itself is tested by classic methods, described, for example, in the work by Neizvestny and Pimonov (1978). Besides this, we necessarily test the photometer against the requirements of the "MANIA" experiment, to define how much it affects the Poisson characteristics of an incident flux.

The tests of "QUANTOCHRON 3" type instruments show that both modifications do not significantly distort y2- and d2-functions.

Fig. 7 shows samples of y2-functions for the dead-time region. The data was taken from the same photometer. Analysis of the curves allows us to conclude that dead time of about 500 ns is characteristic of "QUANTOCHRON 2" itself. As far as "QUANTOCHRON 3" is concerned, our laboratory tests showed that it is possible to measure time intervals as low as 60 ns. Hence we infer that the dead time of a system "photometer + QUANTOCHRON 3" is due to the photometer itself. Photon detectors with a faster response are thus required to make use of the "QUANTOCHRON 3" short interval capability.

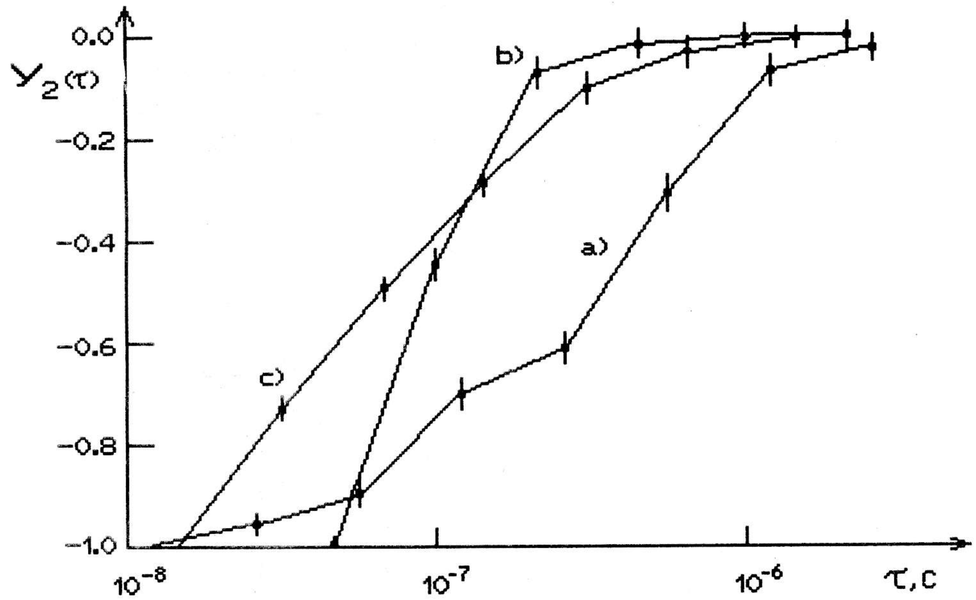

Fig.7. Y2-function samples for dead--time regions:
a)"QUANTOCHRON 2";
b)"QUANTOCHRON 3/8";
c)"QUANTOCHRON 3/16".

The successful tests allow us to conclude that the quality performance of the instrument is adequate for variability search experiments and the investigation of light curves of flare stars. However, when preparing for the observation of strictly periodic objects, one should provide long-term stability for the cycle and nonius frequency generators of the instrument, and study the extreme temporal resolution which can be achieved for many periods of light curves being superimposed. The technique for such an investigation is described in the work by Shvartsman et al. (1988). Here we consider it worthwhile to present only the results of extreme resolution tests of different time-to-code encoders (Fig. 8).

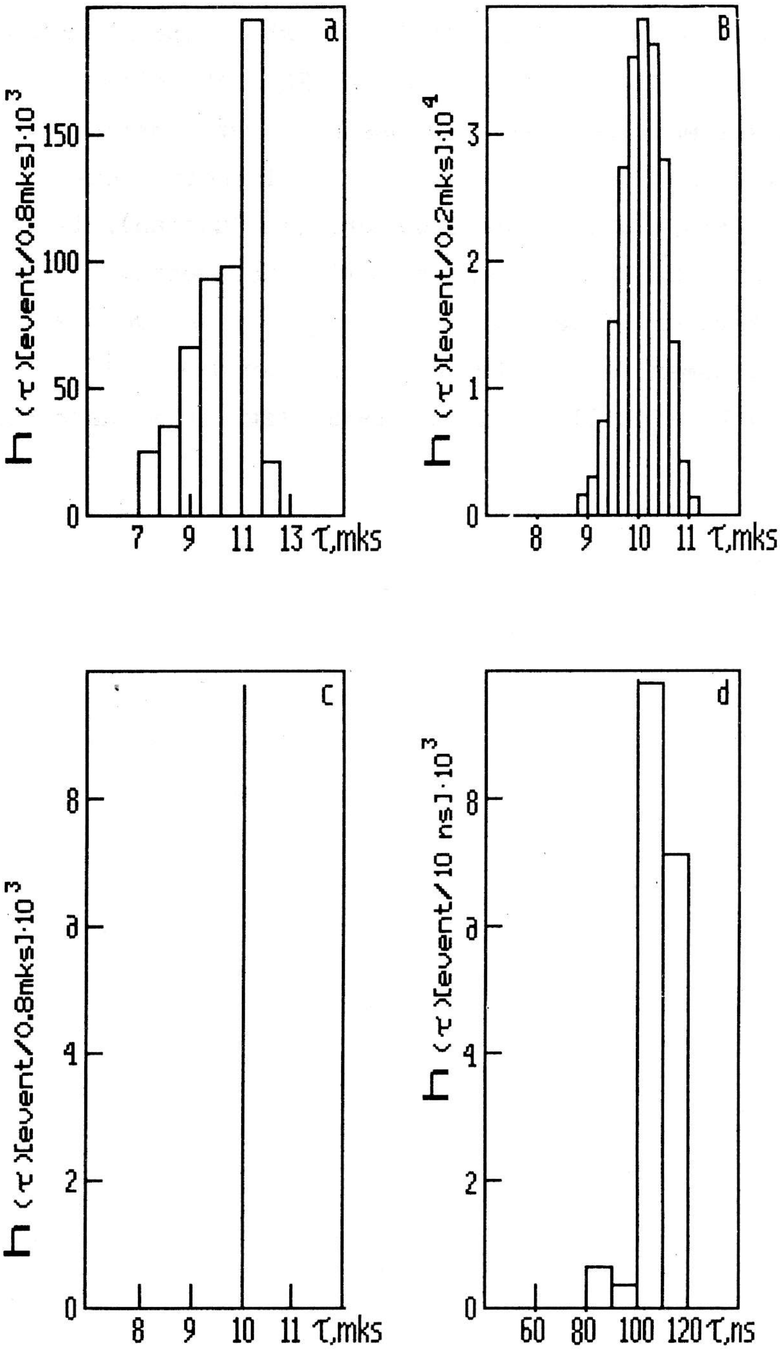

Fig.8. Histogram of dispersion of intervals of the standard frequency near the expected interval value;
a) "QUANTOCHRON 2" corrected for temperature drift of its interval clock;
b) after interpolation of counts against second marks of the observatory's time service;
c),d) "QUANTOCHRON 3/16" data

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