SAS FAMILY OF HYDROSTATIC LEVEL AND TILT SENSORS FOR SLOW GROUND MOTION STUDIES AND PRECISE ALIGNMENT

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1. INTRODUCTION

The design and principle of operation of a family of hydrostatic Level and Tilt monitors (SAS & SAST) is described. These devices are intended for investigation and measurement of components movement of particle accelerators and storage rings and relative movement of ground parts. The SAS type monitor is intended for vertical displacement measurements in the 5 mm displacement range with a resolution about 0,2 μm. In addition, the SAST monitor has a two-coordinate tilt sensor. The range of tilt angle measurement is ± 17 milliradians with sensitivity better than 0.05 milliradian. All the monitors have modifications for operation both with “fully-filled” tubes and with “half-filled” tubes of the hydrostatic leveling system. The electronics of the monitor has a built-in microcontroller to provide measurements, initial calculation of signals and calibrating tests of electronics. The RS-485 interface is used for the data acquisition system. The principle of operation of the monitors, their parameters and methods for organizing the hydrostatic leveling system as well as data acquisition system codes are given in the report. Some examples of monitor usage at SLAC and FNAL are presented.

In accordance with the program of collaboration between BINP, Russia and FermiLab, SLAC from the USA, the development of the Slow Ground Motion Measuring Systems and of the components for them is in progress. The goals of the collaboration is to develop a high-resolution system and to perform corresponding measurements in the Fermilab Main Injector tunnel, in the dolomite Aurora mine, and in the SLAC PEP-II tunnel [1, 2]. These areas represent three different geological sites, so it is interesting and useful to analyze experimental results and to develop conclusions and proposals for the future accelerators and/or storage rings. The Systems include Hydrostatic Level Measurement System, Seismic Measurement System, Operator Board and DC Power supply sources.

This report has a goal to describe only the SAS and SAS-T Sensors and their applications. For these Sensors we had accepted the principle based on capacity measurement:

- To measure the hydrostatic level in vessel
- To use the capacitance between sensing electrode and liquid surface as an variable parameter
- To use the water as a liquid media inside the vessel
- To use stainless steel for the sensors body.

In addition, the SAS-T Sensor is arranged with the two special channels of two coordinates tilt measurement.

We also took into account that two kinds of configurations of the Hydrostatic Leveling Systems widely exist: first one is based on tubes fully filled with water, another one on the half filled tubes. Sketch schematics of Sensors for both of them is presented at the Fig.1 below.

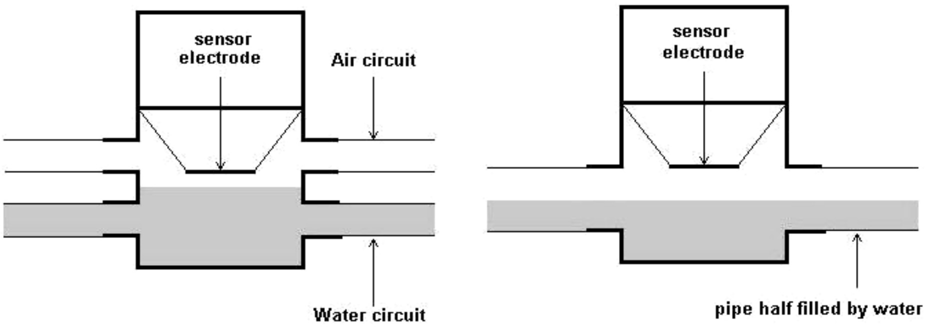

Fig.1 Base schematics of Sensors hydraulic circuit

First our configuration had four vessels ports (two for liquid and two for air) using to operate with plastic pipes (I.D.=12 mm, O.D.=14 mm); second one, as we can imagine firstly proposed by S. Takeda [3], has two vessels ports using pipes (I.D.=20 mm, O.D.=22 mm) half filled with water and all system should be horizontal enough to keep water-air connection all along the pipe. Now we have also the design with 50 mm O.D. In addition the design with external T - air connector is developed.

2. CAPACITANCE BASED METHOD OF LEVEL MEASUREMENTS

Several technologies can be used for measuring liquid level inside vessel. For accurate measurements, capacitance-based sensing is an excellent method. The operating principle is to create a capacitor with the liquid surface being one electrode and the sensor electrode being another electrode of the capacitor, the capacitance of which is measured in order to derive the distance between these two electrodes.

So the instrumentation on top of the vessel is a capacitive sensor that measures the absolute vertical distance between the sensor and the water free surface in vessel.

Let us remind how we can define the distance between a free water surface and sensor electrode due to measurement of capacitance between sensor and vessels surface.

Let us take a simple flat model (Fig.2): sensor electrode and bottom of vessel with water level between them create two serial connected capacitors C1 (air medium) and C2 (water medium).

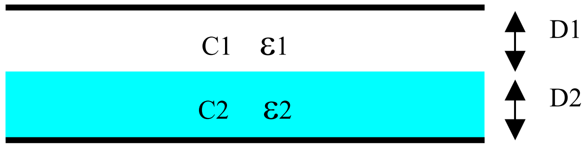

Fig.2 Capacitors in level sensor; ε_1 ε_2 are permittivities; D_1 D_2 –distances

Here $C_1 = {A_1\varepsilon_1}/{D_1}$ $\quad C_2 = {A_2\varepsilon_2}/{D_2}$

A_1, A_2 - coefficients determined by electrodes surface area and its shape.

The electronics connected to the sensing electrode, can sense the total capacitance C that is equal to: $\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_2}$

This relation can be reconfigured to determine the distance D_1 that is determined as air gap value: $D_1=\frac{A_1\varepsilon_1}{C(1-k)}-D\frac{k}{(1-k)}$

where $D=D_1+D_2$ - total distance; $A_1 \approx A_2$ - the geometry coefficients;

$k=\frac{A_1\varepsilon_1}{A_2\varepsilon_2}$ - coefficient.

Let us remark that $k<<1$ because the permittivities are: $\varepsilon_2 \approx 80$, $\varepsilon_1 \approx 1$.

One of disadvantages of the earlier versions of Hydrostatic Level Sensors is the analogous (voltage) presentation of output signal. As it is well known, this circumstance creates some difficulties in measurements. Some bridge schematics allow to get stable transfer function coefficient, but drift of zero level is more difficult and complicated part of analogous circuits.

As a result of some of our investigations of different circuitry approaches, we had decided to develop the sensor with the ***C => F*** conversion. As a base method we had chosen the idea presented at the work of Ferry N. Toth and Gerard C.M. Meijer [4]. Their circuitry principle is presented at Fig.3. It is based on the possibility of circuit to be calibrated during each measurement.

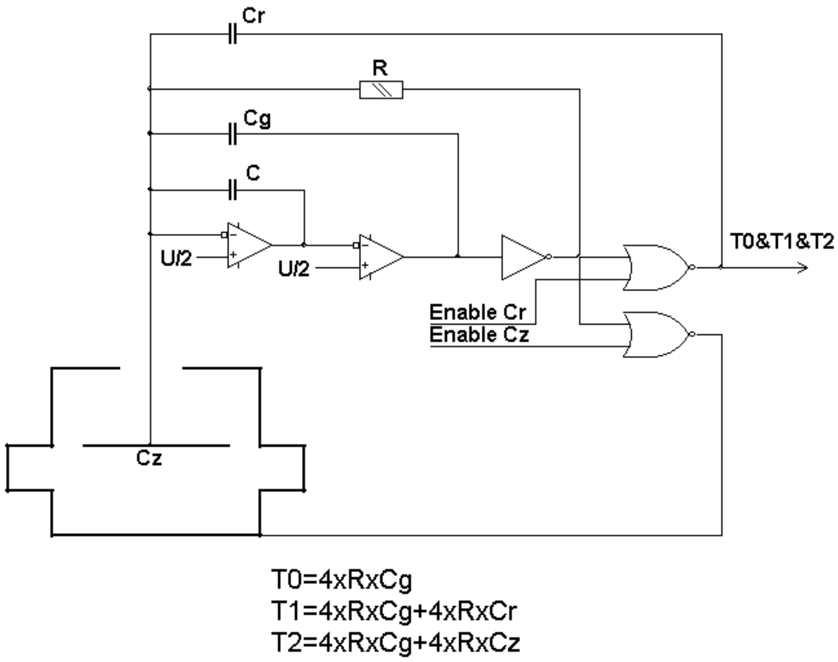

Fig.3 Ferry N. Toth and Gerard C.M. Meijer C => F converter

«C => F» converter is an RC-generator with oscillating frequency determined by it's internal parameters, including Capacitors C_g , C_r and C_z .
Oscillating period is T_0 when both Gates, «Enable C_r» and «Enable C_z», are switched OFF (Capacitor C has negligible influence on the period):

$T_0 \approx 4RC_g$

It became T_1 when Gate pair is installed into the position «Enable C_r»:

$T_1 \approx 4RC_g + 4RC_r$

For Gate pair installed into position «Enable C_z»:

$T_2 \approx 4RC_g + 4RC_z$

Switching ON/OFF of the Gates into all of three positions in turn, we will shift the oscillating frequency range of generator. And what is more, due to comparing of these periods (frequencies) we can take into account or eliminate influence of most of the circuitry elements instability on resulting measurements of distance (D1 – see Fig.3.1.2-1) between free water surface and the sensor electrode:

$$\frac{T_1 - T_0}{T_2 - T_0} = \frac{C_r}{C_z} \quad \Rightarrow \quad \frac{T_1 - T_0}{T_2 - T_0} = M_1 D_1 + M_0 D$$

In our practical case period T_0 was chosen approximately as $T_0 \approx 11$ µsec. T_2 varies from 11 to 18 µsec depending on water level in vessel. The time value of 2^{14} periods is measured to determine the period of each position.

In addition, temperature of vessel is measured for thermal dilation corrections. Temperature of internal electronic circuit of sensor is not stabilized.

3. TILT MEASUREMENTS

For tilt measurements we use the electrolytic tilt sensors of SH500055-A-009 type, manufactured by Spectron Glass and Electronics Inc. This type of sensors is capable of producing extremely accurate pitch and roll measurements in a variety of applications. They provide excellent repeatability, stability, and accuracy. SH500055-A-009 sensor are simply integrated into the SAS-T sensor body. A principle of the sensor design one can understand from the Fig.4.

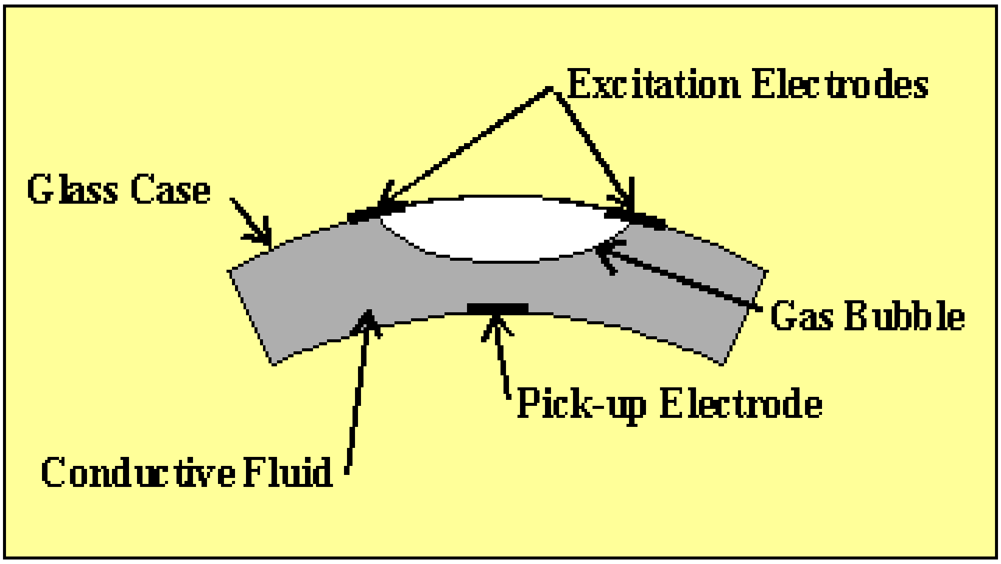

Fig.4 Principle of electrolytic tilt sensor operation

The sensor consists of Glass Case with three integrated Electrodes: two are Excitation Electrodes and one Pick-up Electrode. Inside Glass Case there are Conductive Fluid and Gas Bubble. As the sensor tilts, the Gas Bubble remains at the top level due to gravity. The Fluid is electrically conductive, and the conductivity between the two electrodes is proportional to the length of electrode immersed in the fluid. Electrically the sensor is similar to capacitive half-bridge with capacitors changing in proportion to tilt angle.

We use for our design the hand - picked SH500055-A-009 type sensors. Main technical characteristics of them are presented in Table 1.

Table 1. Main characteristics of SH500055-A-009 sensor (hand – picked)

Parameter	**Unit**	**Value**
Total tilt angle range	Arc degrees (mrad)	±1 (±17.5)
Linear range	Arc degrees (mrad)	±0.5 (±8.7)
Resolution	Arc degrees (mrad)	< 0.0001 (< 0.00175)
Zero level repeatability	Arc degrees (mrad)	< 0.0008 (< 0.014)
Symmetry at half linear scale	%	<2
Impedance at 1 kHz at zero point	kOhm	1
Operating temperature	°C	-54 ÷ +125
Zero level typical drift (12 hrs @ 25°C)	Arc degrees (mrad)	< 0.0005 (< 0.0087)
Scale factor temp. Coefficient typical	1/K	0.006

The functional circuit diagram of tilt measurement principle is presented on Fig.5.

It was accepted that the C*(tilt)* to U conversion – one of popular configurations with the AC bridge circuit – will be used. The sensor can be used as one half of the bridge with the full excitation voltage across the sensor. Second half of bridge is organized as a reference voltage that is approximately equal to half of excitation voltage amplitude. The main features of the circuit:

- A square wave of excitation;
- A phase sensitive voltmeter (synchronous voltmeter) is hooked up between the Pick-up Electrode and of the Reference point. This voltage is proportional to the tilt angle. The output is zero volts if the sensor is aligned with the vertical plane. Any deviation from the alignment increases the output voltage, that is measured by ADC. The tilt direction is determined by the phase between the Excitation Electrode and the Pick-up Electrode. The phase switches from 0° to 180°.

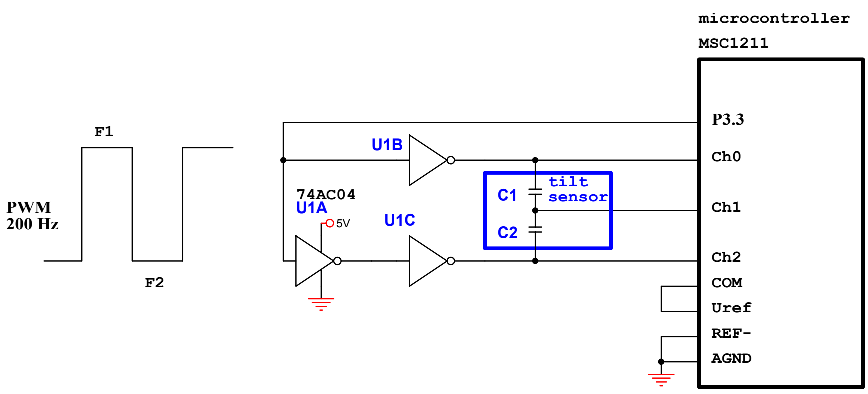

Fig.5 Circuit diagram of tilt measurement principle

Measuring of the voltage level of the U1B, U1C, C1/C2 middle point and Uref≈Ups/2, where Ups means supply voltage of the output inverters, we can calculate the displacement value. The measurements are performed during each halfperiod of 200 Hz PWM clock frequency, so we can determine the phase (direction) of displacement and to get enough number of clock-measurements for statistic increasing of the measurements accuracy. The "one measurement" period duration is 240 ms. Measurement of U1B and U1C allows us to calibrate transfer coefficient during each measurement period and the AC mode of input voltage allows exclude the ADC zero displacement and its drift.

4. SAS-T ELECTRONIC CARD

All the above-stated circuitry approaches are combined into one electronic card. The functional circuit diagram of SAS-T electronics is presented on the Fig.6. All the electronics is operated under the Flash microcontroller of MSC121x type of the Texas Instruments. The last is controlled by the commands of Operator Board computer via RS-485 driver. Earlier versions were based on microcontroller AT89S8252 of Atmel Corp.

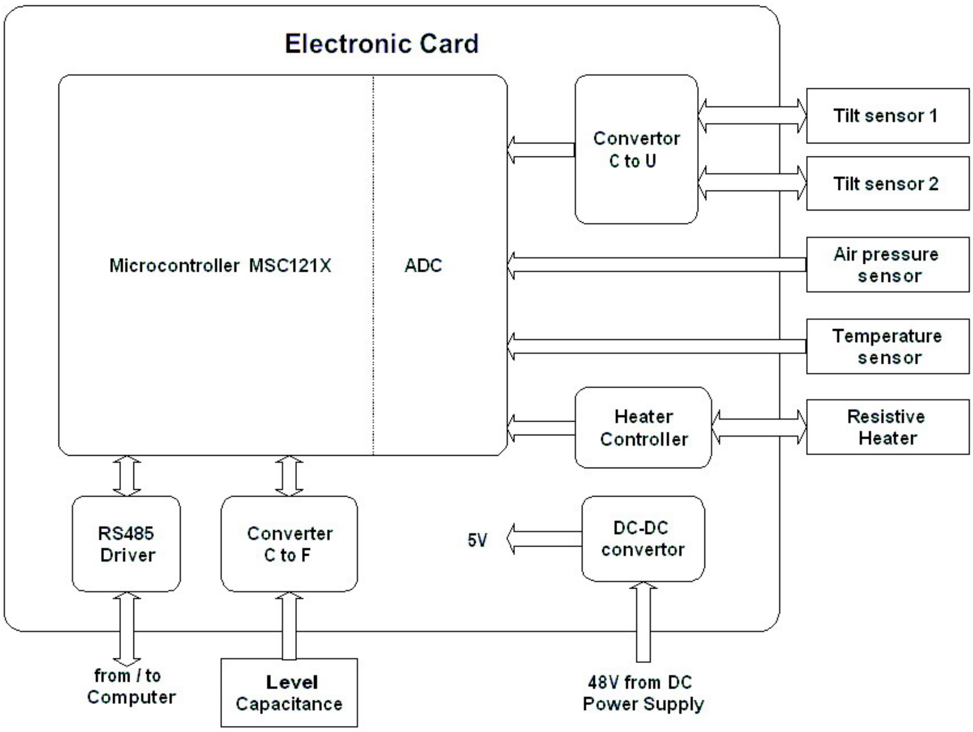

Fig.6 Functional circuit diagram of SAS electronics

The algorithm of autonomous operation of microcontroller is distributed inside its internal flash memory. Another components of electronics present (include):

- ***C(level)* => *F*** converter for conversion of water level depending capacitance *C* and reference capacitances into frequency *F*;
- ***C(tilt)* => *U*** converters of the Tilt Sensor - 1 and Tilt Sensor - 2 signals to measure roll and pitch independently.

- Absolute external air pressure sensor of ratio-metric MPX4115A type;
- Ratiometric temperature sensor for monitoring of the vessel body temperature; AD22100 type monolithic silicon temperature sensor of Analog Device co is used. Temperature measurement resolution is about 0.05K.
- Resistive heater to support and to stabilize the electrodes over-temperature regime against the water temperature. This channel prevents the electrode surface against the dew.
- All of the mentioned signals are converted by 8 - channeled 16 bit ADC, that is a part of microcontroller;
- The resulting frequencies are counted by microcontroller via its counting input. The clock of counting is determined by the program and by clock quartz oscillator (22.11 MHz).
- The resulting digital data are transmitted via standard serial interface RS485 to the PC computer. RS485 driver is isolated from all other electronics of SAS-T and can be used in duplex and half-duplex modes.
- All the SAS-T electronics requires +5V Power supply. This voltage is produced by on board switch mode DC/DC power converter. Its input voltage is as high as 48V that allow us to decrease the voltage drop on the powering line when number of sensors are installed and connected in series to one cable.

All the described electronics is placed at one PCB with diameter 76 mm, that is mounted at the top position of SAS-T monitor (Fig. 7).

Fig. 7 Electronics card of SAS

5. SAS-T PROTOCOL OF DATA EXCHANGE CODES

The SAS and SAS-T microcontroller command system is compatible with the ***Field Point F1001*** command system of the National Instruments Corporation. All the procedures are activated after ***"power ON"*** of the system. After this the SAS waits for the command ***"Power Up Clear"*** and in accordance with the ***Field point*** don't accept another broadcast commands.

Some examples of commands:

A – Power Up Clear – operation start after switching ON of the Power Supply;
S – the beginning of measurements;
I – is a request on data reading of water level measurements;
O – is a request on data reading of tilt (roll) measurements;
H – is a request on data reading of tilt (pitch) measurements;
T – is a request on data reading of temperature measurement;

B – baude rate of serial link; initial rate 9600;
P – is a request on data reading of air pressure measurement;
t – Heater power measurements.

All these data are bytes of ASCII code of digital presentation in ***Hex*** format.
The SAS-T answers ***"Error"*** in case of mistake in any individual command.
SAS-T can recognize four types of mistakes in operation inside the messages.

6. SAS FAMILY DESIGN

The BINP Hydrostatic Level Sensor is designed as a device with two independent parts: upper one is with electronics and lower part filled with the water. Lower volume is designed in three modifications:

a) Vessel-1 Model has separate pipes for connecting with air tubes and 12 mm water tubes. This Model should be used into the system with "fully-filled" lower tubes.
b) Vessel-2 Model has supplied with pipes with relatively big diameter to be connected into the system with 22 mm "half-filled" tubes.
c) Vessel-3 Model is also developed for "half-filled" tubes operation but with pipe diameter about 48mm.

All of these vessels can be done as SAS and SAS-T modifications. SAS-T Model is equipped with one or two tilt sensors for pitch and/or roll measurements.

Fig.8 presents assembly drawing of SAS-2 Model and view. Design consist of two parts: lower part and upper part. The lower part includes the body (1) and two pipes (2) for water communication of 22 mm diameter, oriented into two opposite directions. There are a cylindrical hole for temperature sensor inside the bottom of lower volume (not shown) and four screw holes for the SAS installation purposes.

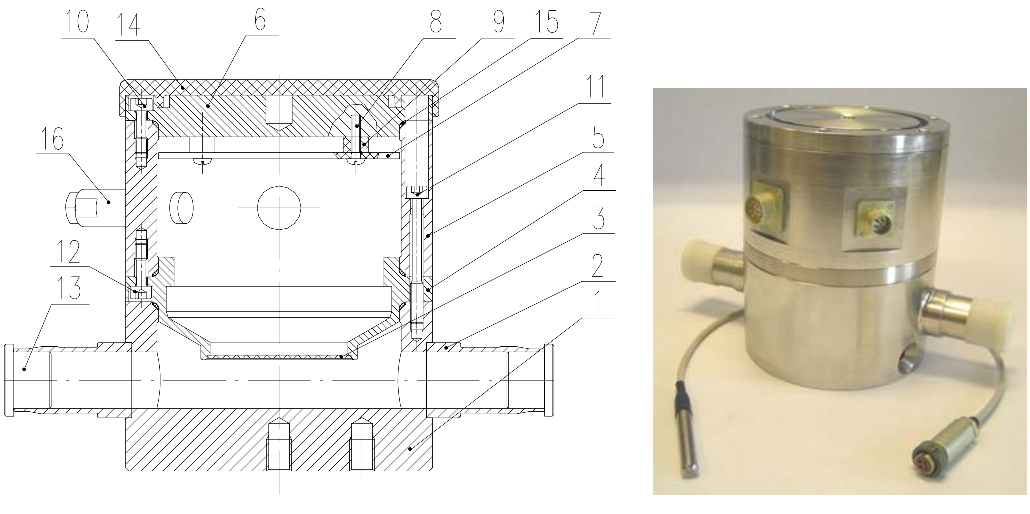

Fig.8 Design drawing of the SAS-2

Upper part includes the body (5), the iron ring (4) for holding the ceramic plate (3) with Sensing Electrode and resistive Heater; printed circuit board (7) with SAS electronics and cover (6). The iron ring and the cover are fixed with waterproof connection to the body by the screws

(10 and 12). Heater is installed to maintain the temperature of ceramic plate slightly higher than of water and air temperature inside the vessel to exclude the appearance of water condensate on the ceramic surface. Two connectors, the first of PCГ4TB (16) type and the second one of PCГ10TB type (not shown), are used to connect the temperature sensor to the SAS electronics and the SAS digital interface to the based on RS-485 LAN correspondingly.
All the body parts are done with stainless steel.

The screws (11) are used to join the upper part with lower one.

7. RESULTS

Main parameter list of the SAS-monitors are presented at the Table 2 below.

Table 2. SAS family main parameters

Parameter	Unit	SAS-x	SAS-T
Vertical displacement dynamic range	mm	5	5
Uncalibrated displacement dynamic range	mm	2 -- 16	2 -- 16
Displacement resolution (one minute averaging)	mcm	0,05	0,05
Transfer function temperature stability	ppm/K	300	300
Number of tilt channels	--	--	two
Tilt measurements dynamic range	mrad	--	17,45
Tilt resolution	mrad	--	0.01
Tilt transfer function temperature stability	1/K	-	0.006
Data acquisition maximal frequency	Hz	2	0.5
Supplying voltage	V	48 (36-60)	48 (36-60)
Power consumption	W	<2.5	<2.5
Monitor diameter	mm	98	98
Height (depending on vessel type)	mm	125=>137	125=>137

Up to now the BINP team had manufactured, tuned and installed at the SLAC and FNAL sites more than 70 SAS-monitors. The typical picture of monitor resolution is presented at Fig.9 and Fig.10.

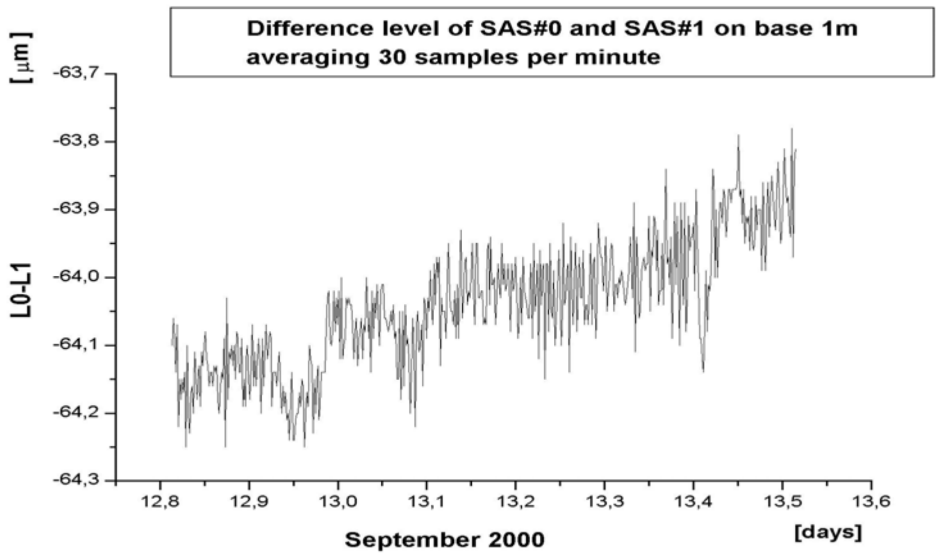

Fig.9 SAS resolution presentation

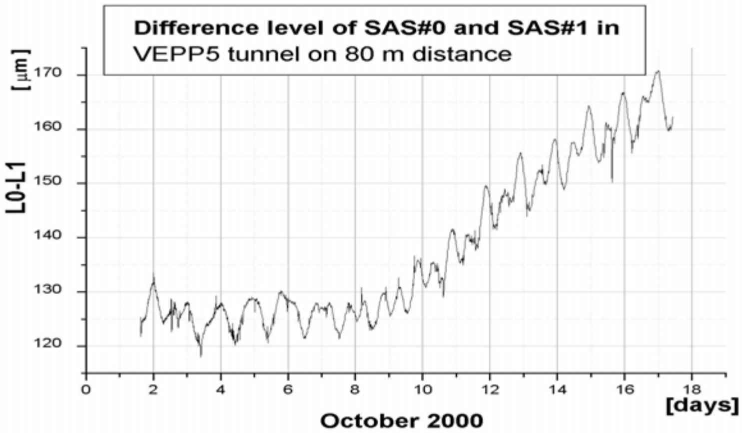

Fig.10 SAS measurement example of ground motion

The first one shows difference of two monitor measurements when they are installed closely one to another; next picture presents the measurement of the moon and the sun influence on ground motion. Monitors are installed at distance 80m. The pictures at Fig.12 present the parts of SAS monitor.

Fig.12 Partly disassembled SAS monitors

8. REFERENCES

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