THE ULTRASONIC LEVEL SENSORS FOR PRECISE ALIGNMENT OF PARTICLE ACCELERATORS AND STORAGE RINGS

A.G. Chupyra, G.A. Gusev, M.N. Kondaurov, A.S. Medvedko, Sh.R. Singatulin

BINP, 630090, Novosibirsk, Russia

The report describes the newly developed Ultrasonic Level Sensors (ULS),
their principle of operation, design and some test results,
obtained at BINP and SLAC test stands. (*)[1]

(*) Work is supported by SLAC

1. Introduction

Alignment of large accelerator machine components with high accuracy is important task now.

In accordance with the program of collaboration between BINP, Russia, SLAC and FNAL, USA

Development of the Hydrostatic Level Sensors :

Capacitance based (SAS) and

Ultrasonic based (ULS)

are parts of this joint program.

The presented Ultrasonic Level Sensors (ULS) type monitor is intended for vertical displacement measurements:

5 mm displacement range;

0,2 μm resolution (about);

5.0 μm accuracy

Half filled tubes;

For the development we had based on the next, widely used principles:

- To measure the hydrostatic level in communicating vessels;
- To use the water as a liquid media inside the vessels;
- To use stainless steel for the monitor body

Each ULS vessel is equipped with:

- the piezoelectric transducer of Panametric or Krautkramer type;
- the temperature sensor ;
- electronics box.

The electronics has:

- fast and precise Time-to-Digital converter (TDC)
- microcontroller
- built-in interface
- DC/DC converter

There are two types of ULS prototypes:

ULS-PR => with Panametric Transducer and RS-485 Interface

ULS-KE => with Krautkramer Transducer and *PoE* (Power – over – Ethernet) interface

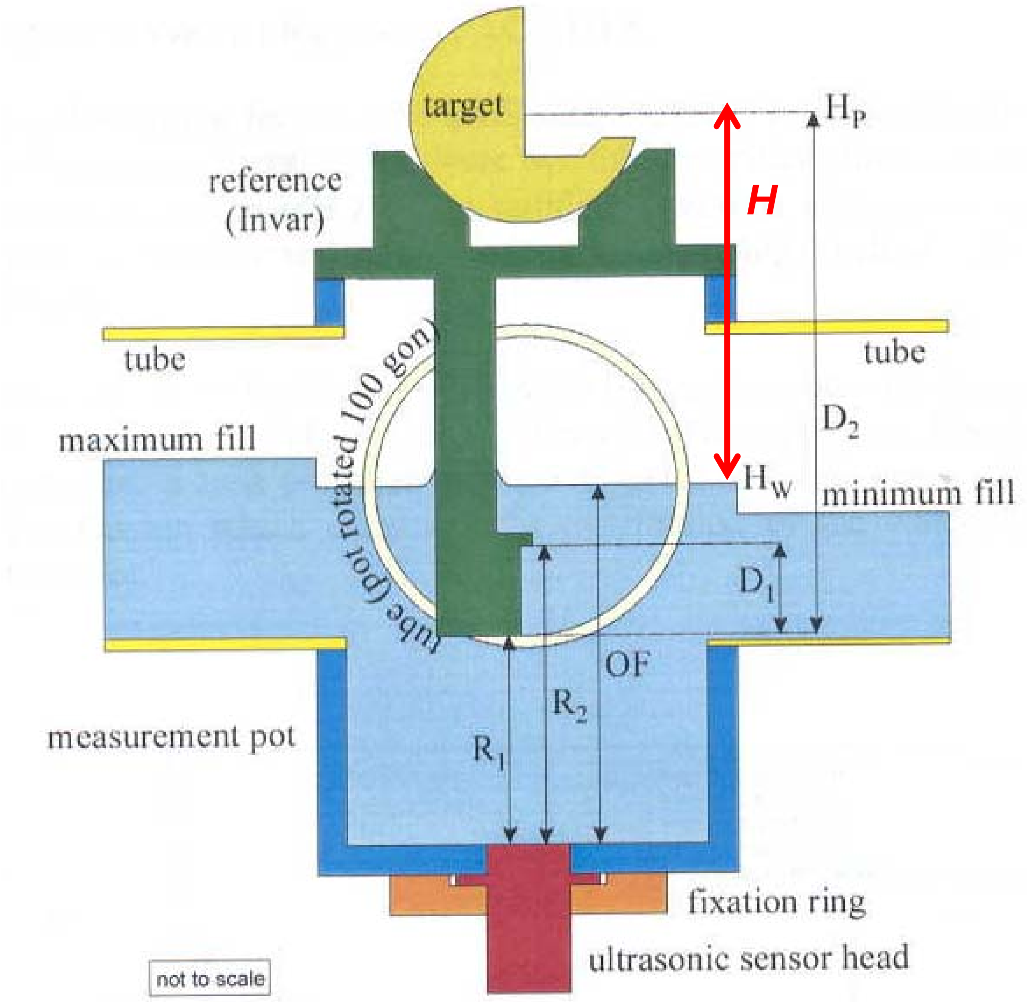
2 ULTRASONIC BASED METHOD OF LEVEL MEASUREMENTS

The ultrasonic hydro-location is well known and widely distributed method of distance measurements for many applications.

One of precise methods:

Markus Schlösser, Andreas Herty **"High precision accelerator alignment of large linear colliders – vertical alignment"** ***Proceedings of the 7th IWAA, Spring-8, 2002.***

Their idea is to locate not only the water surface in a vessel, but also two addition surfaces with calibrated distance between them and at the calibrated distance to alignment reference target.



$$H = D_2 - D_1 \cdot \frac{t_{of} - t_1}{t_2 - t_1}$$

Principle of organizing the reference surfaces at the ULS

(Picture is from the **M. Schlösser & A. Herty** ***report)***

H - distance from the water surface Hw ***to external reference surface (point)*** Hp

Some basic principles

- **Pulse-echo method for water level measurements:**
- **Determine the location of free water surface in a vessel**
- **Determine the location of reference reflective surfaces**
- **Accurately measuring the time required for a short ultrasonic pulse, generated by a transducer (sensor head), to travel through a thickness of water, to reflect from the free water surface or from the reflective surface, and to be returned to the transducer.**

- **The result is expressed by the relation:** $D = V \cdot t / 2$
- ***D*** **is the distance,**
- ***V*** **is the velocity of sound waves in water,**
- ***t*** **is the measured round-trip transit time.**

Special transducers => immersion transducers

- Transducers are designed to operate in a liquid environment
- They usually have an impedance matching layer that helps to radiate more sound energy into the water and to receive reflected one.
- Immersion transducers can be equipped within a planner or focused lens.
- A focused transducer can improve sensitivity and axial resolution by concentrating the sound energy to a smaller area.
- The sound that irradiated from a piezoelectric transducer does not originate from a point, but from all the surface of the piezoelectric element.
- Round transducers are often referred to as piston source transducers because the sound field resembles a mass in front of the transducer.

Near zone => Far zone

- **The ultrasonic beam is more uniform in the far field zone**
- **The transition between these zones occurs at a distance**

  N → **"natural focus" of a flat (or unfocused) transducer.**
- **This near/far *distance N is very significant:* This area just beyond the near field where the sound wave have maximum strength.**

- ***Optimal measurement results will be obtained when reflective surfaces are close to N area:***
- ***N < D < 2N***

- ***This requirement determines the minimal distance from transducer to target surfaces.***

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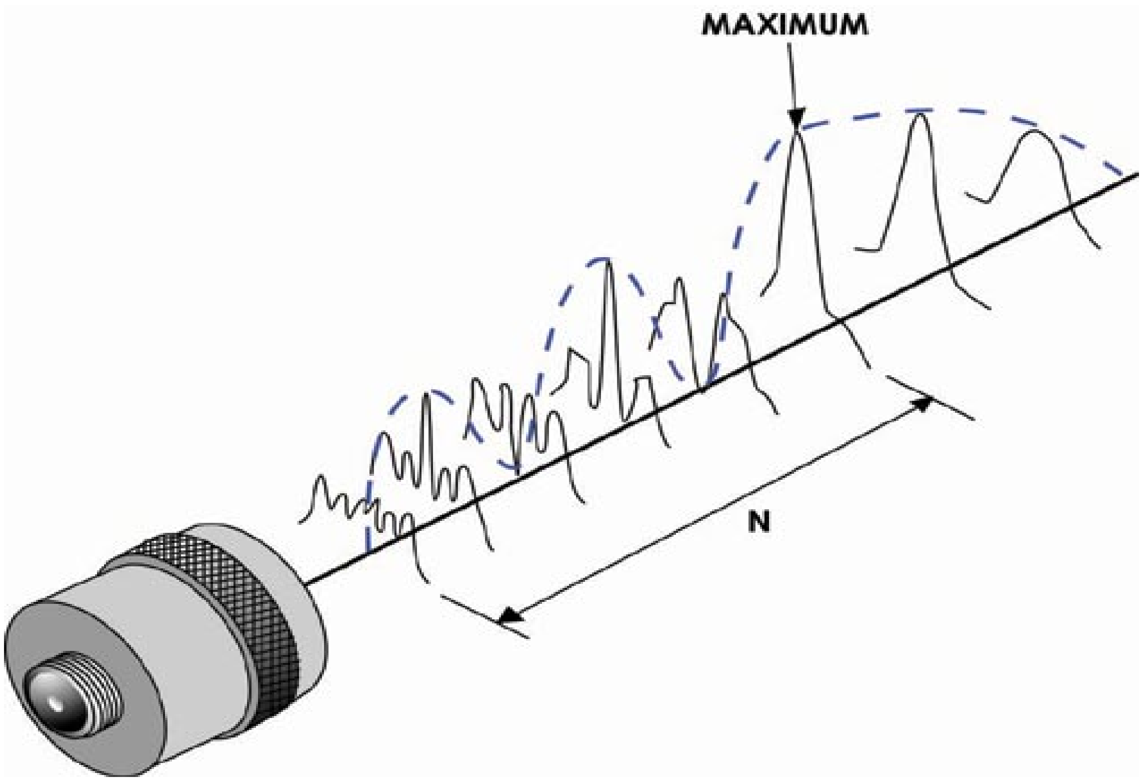


For a piston source transducer with:

Diameter ***d*****,**

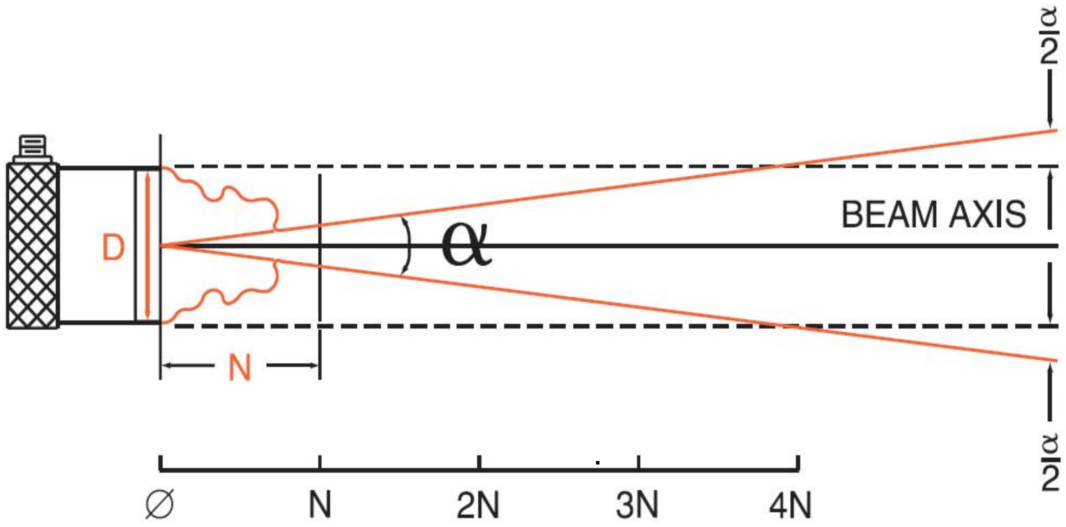
Central frequency ***f*****,**

Sound velocity ***V***

the estimation of the near/far field transition point:

$$N = f \cdot (d/2)^2 / V$$

Sound field pictures of the typical piezoelectric transducer



A simplified view of a sound beam for flat transducer

$$Sin(\alpha/2) = 0.514 \cdot V/(d \cdot f)$$

(The coefficient corresponds to - 6dB intensity decreasing)

Unfocused immersion transducer parameters **Table 1**

Parameter \ Transducer Type	Units	V310-RU Panametric	H10 KB 3 Krautkraemer
Central frequency	MHz	5.0	10.0
Bandwidth	%	>70	<40
Transducer diameter	mm	6.35	5.0
Beam spread angle $\alpha/2$	Degree (rad)	1.365 (0.0243)	0.884 (0.0154)
near/far distance N	mm	33.6	41.7

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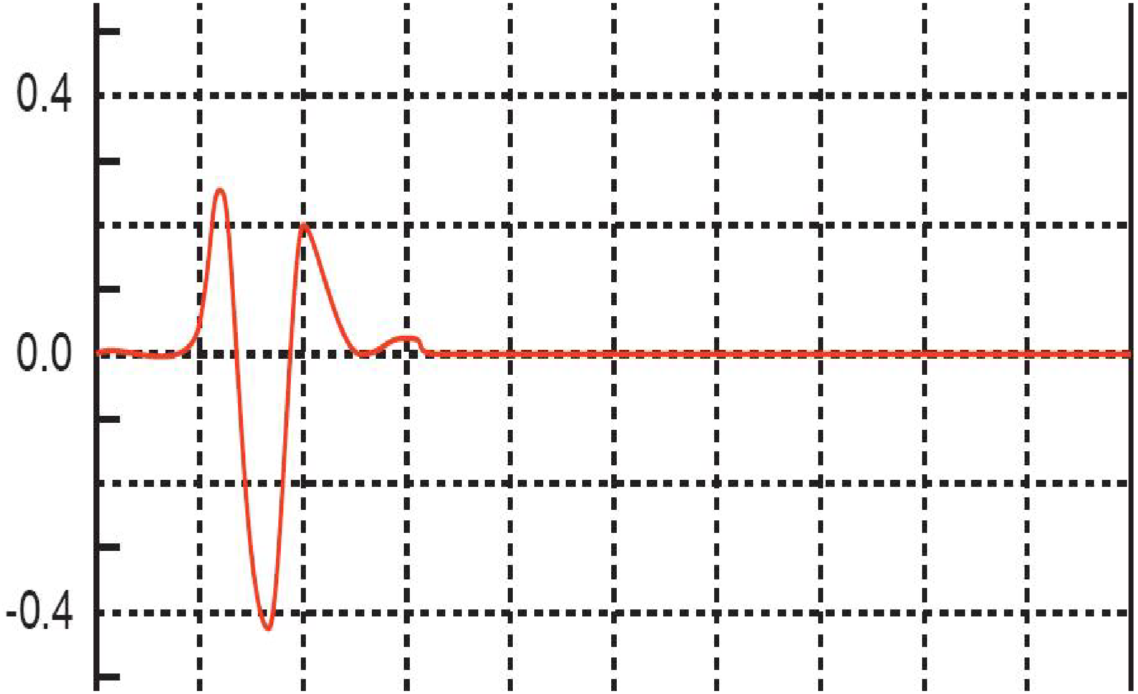


Time: 0.2microsec/div

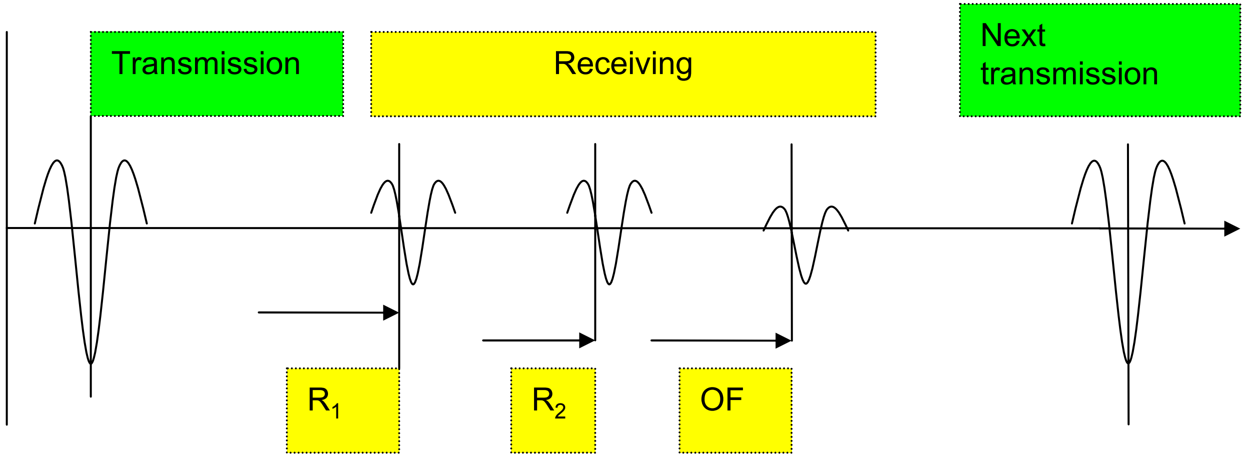
Amplitude: 0.2 V/div

Typical time response of V310-RU transducer

3 ULTRASONIC SIGNALS AND ULS ELECTRONICS

$$H = D_2 - D_1 \cdot \frac{t_{of} - t_1}{t_2 - t_1}$$

The goal of ULS electronics is to measure time intervals with the accuracy as fine as possible and to calculate the resulting values



Time diagram of the transducer operation

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In compliance with the mechanical design of the prototype ULS we should measure three distances: *R1, R2, OF*

Type	***R1***	***2t***	***R2***	***2t***	***OF***	***2t***	***dH***	***dt***
	mm	*µs*	*mm*	*µs*	*mm*	*µs*	*mm*	*µs*
ULS-PR	45	60.69	50	67.43	62	84.3	±2.5	±1.7
ULS-KE	55	74.17	62.5	84.29	75	101.46	±2.5	±1.7

Sound velocity in water equal to 1483m/sec at 20°C.

Displacement resolution 0.2µm => time resolution ± 140picosecond

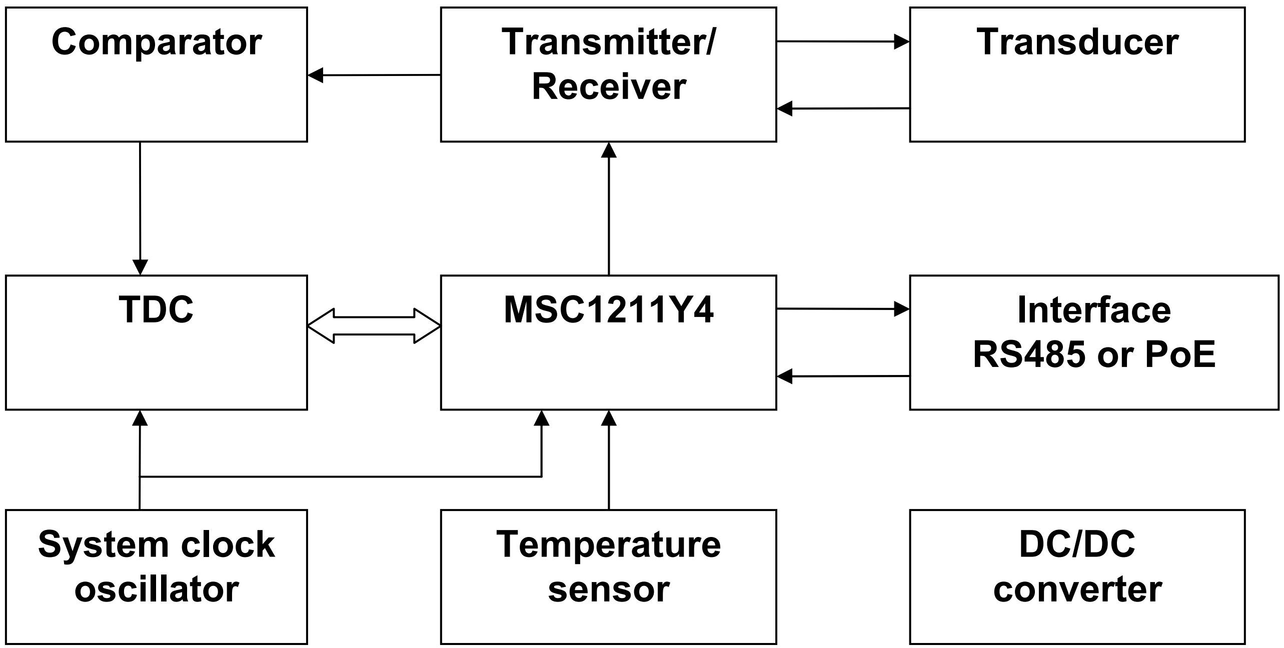
Accuracy about 5µm => accuracy about 3.4nanosecond.
For different systems comparison.

One second averaging time interval for different systems comparison.

The signal repetition frequency at the ULS was chosen 100 Hz.

Time interval measurements

- **The transducers with as high as possible value of operating frequency. We choose 5MHz and 10MHz;**
- **One clock of "Start" for all (three) time intervals to be measured**
- **"Zero level" comparator to fix the arrival time of the reflected pulse;**
- **TDC-GP1 type of the Time-to-Digit Converter with highly precision measurement function.**
- **Microprocessor based electronics for each Sensor to make necessary individual calibrations and processing with signals: storing of measurement results, calculation and averaging them.**



Functional circuit diagram of the ULS electronics

TDC-GP1 of ACAM Corp. → ***Time-To-Digital Converter* -- central chip of the ULS electronics.**

The main features of TDC-GP1:

- **2 measuring channels with up to four independent "Stops" per channel**
- **Typical resolution of 250ps;**
- **Typical resolution of 125ps for mode with one channel;**
- **Nonius method in one channel mode. The result is the sum of different finecount and coarsecount counters;**
- **4-fold multi-hit capability per channel, double pulse resolution typ. 15ns**
- **retriggerable;**
- **2 measurement ranges => a: 2 ns -7.6 μs => b: 60 ns-200 ms;**
- **The 8 events of the two channels can arbitrarily be measured against one another;**
- **Variable edge sensitivity of the measuring inputs;**
- **Internal ALU for the calibration of the measurement result.**
- **Extremely low power consumption.**

Nonius Mode of TDC-GP1

The mode of TDC operation "Measurement Range 2" :

Only 1 channel is available with :

4 possible STOPs in normal resolution (250 ps)

3 possible STOPs in high resolution (125 ps)

In our case we have to measure three time intervals (three Stops against one Start).

Some explanations about Comparator and it’s function

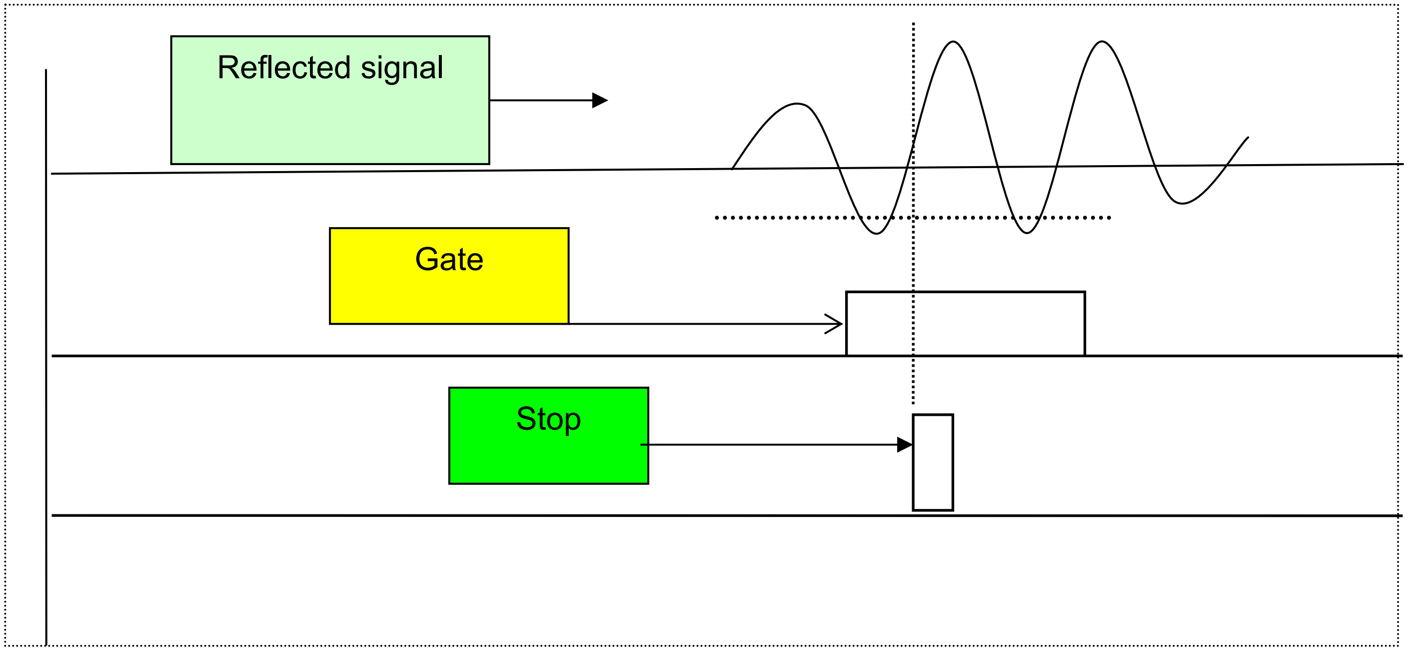
Comparator converts analogous signal of reflected oscillations into the digital “ON/OFF” form.

To avoid the dependence of time measurements from reflected pulse amplitude we had applied the “zero level” comparator.

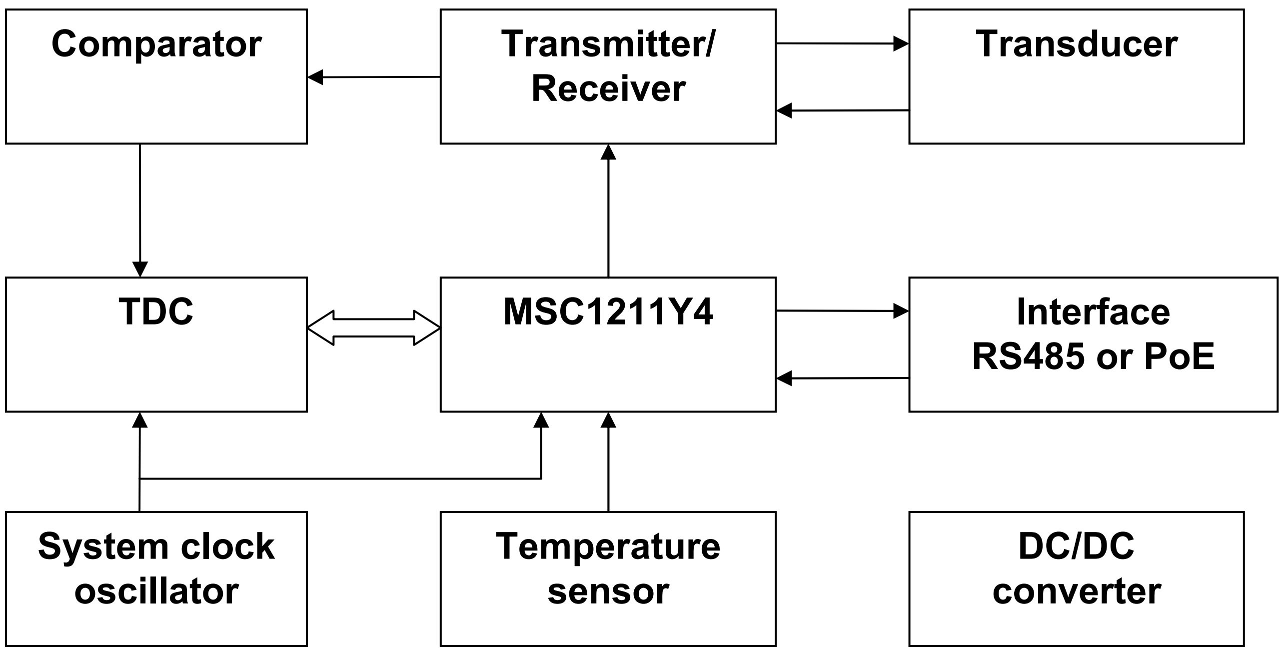
In Comparator the reflected analogous signal, looking like a short bunch of oscillations, enters to the gate.

Gate has predicted time position and pulse duration. It has raw comparator. Main Comparator has zero reference level and sufficiently high gain.

Goal is to fix the “transition to the first positive pulse after first negative pulse with sufficiently large amplitude”.



Time diagram of "zero level" comparator operation



Functional circuit diagram of the ULS electronics

The sequence of operations of the electronics of the ULS

- After power "*ON*" the Microcontroller begin fulfillment of program, placed in its internal memory. At the command of computer (PC) the microcontroller makes measurement cycle.
- It forms start pulses for the Transmitter and TDC.
- The Transmitter generates electrical pulse for Transducer.
- The Receiver takes the reflected signals and sends them to the Comparator.
- The Comparator transforms analogous signals into digital pulses.
- TDC measures time intervals between the start pulse and the pulses coming from the Comparator.
- The Microcontroller gets digital codes from TDC and transforms them for the next transmission to PC computer.
- Number of cycles and clock frequency of PC is determined by system and size of the ULS memory.
- The Microcontroller also can measure temperature of ULS vessel and accordingly temperature of water inside the vessel with help of temperature sensor and inboard ADC. Temperature measurement resolution is about $0.1^{o}C$.

DATA ACQUISITION SYSTEM AND SOFTWARE

- Data acquisition in is organized with the help of standard serial interfaces
- ***RS-485*** for ULS-PR
- ***PoE*** for ULS-KE
- Standard system of commands ***Field Point F1001,*** National Instruments Corp.
- Work under the Widows 2000/XP Operating System.
- External electric circuit has galvanic isolation from all the other electronics.
- The Software will allow continuous processing of hydrostatic level and temperature. It will allow utilization of user-defined data treatment modules and transmitting of the raw data and results of the data processing via standard data exchange procedures.
- All needed adjustment and test procedures are included into the software kit.

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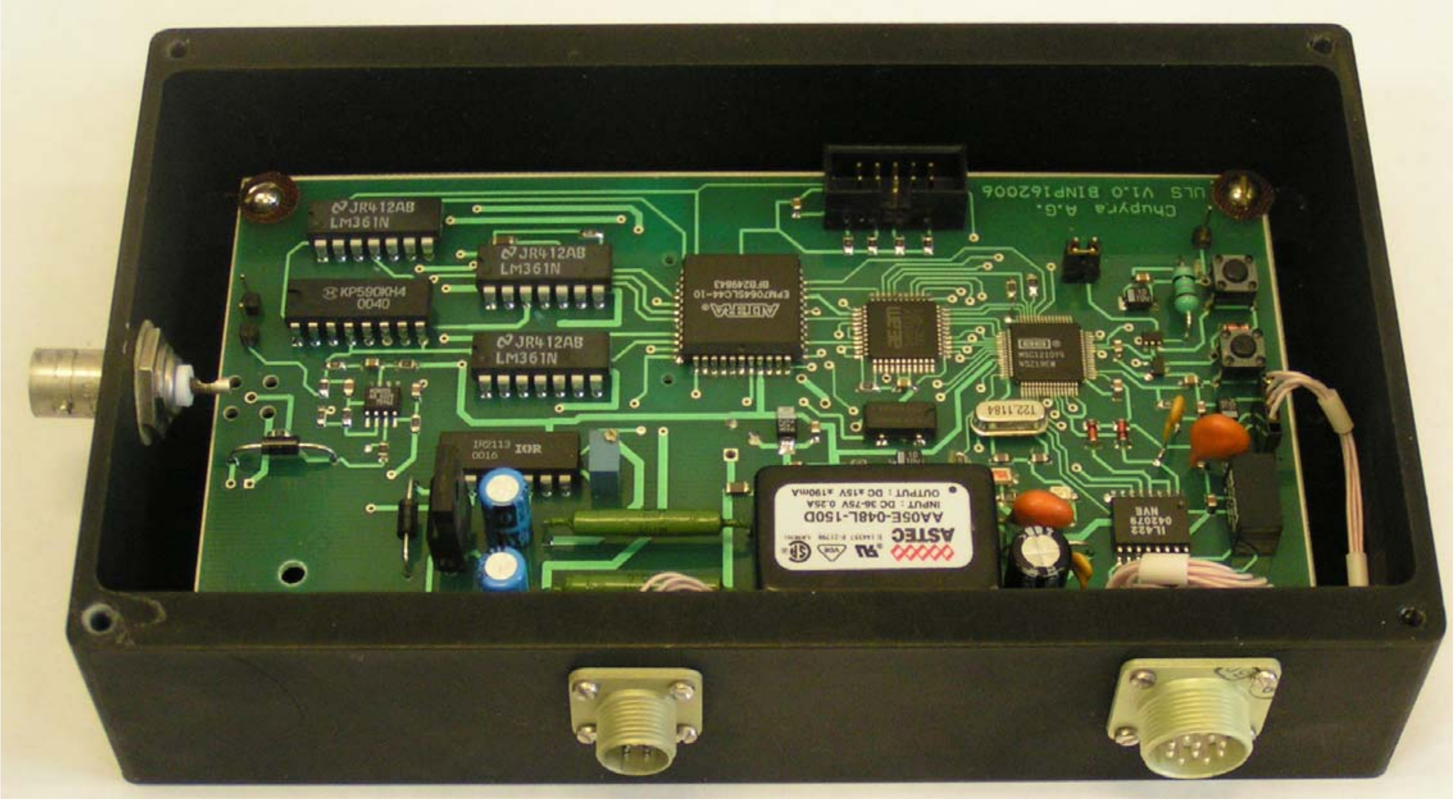

- All the power for the ULS electronics is supplied via DC/DC converter.
- The input voltage of the converter can be in range from 36V to 48V DC.
- Power consumption is about **3W for ULS-PR** and about **4W for ULS-KE.**

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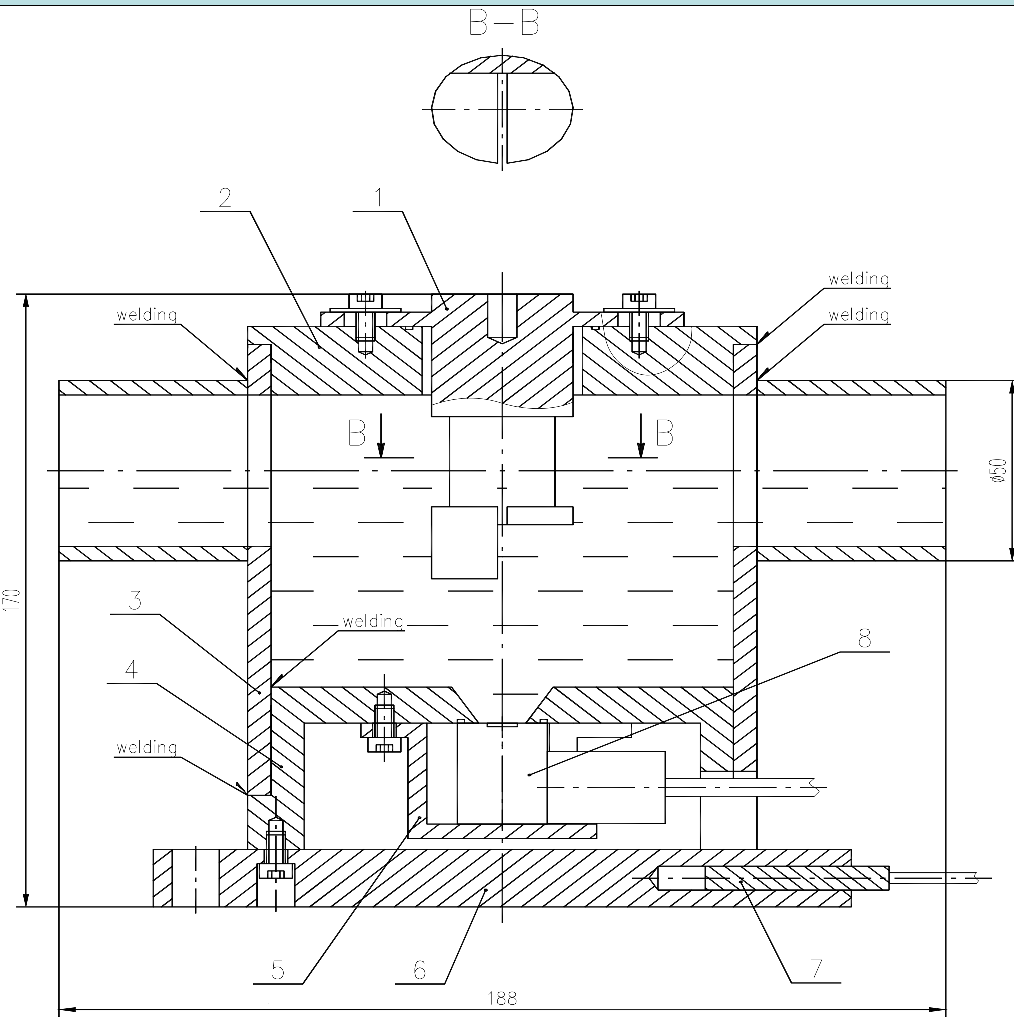
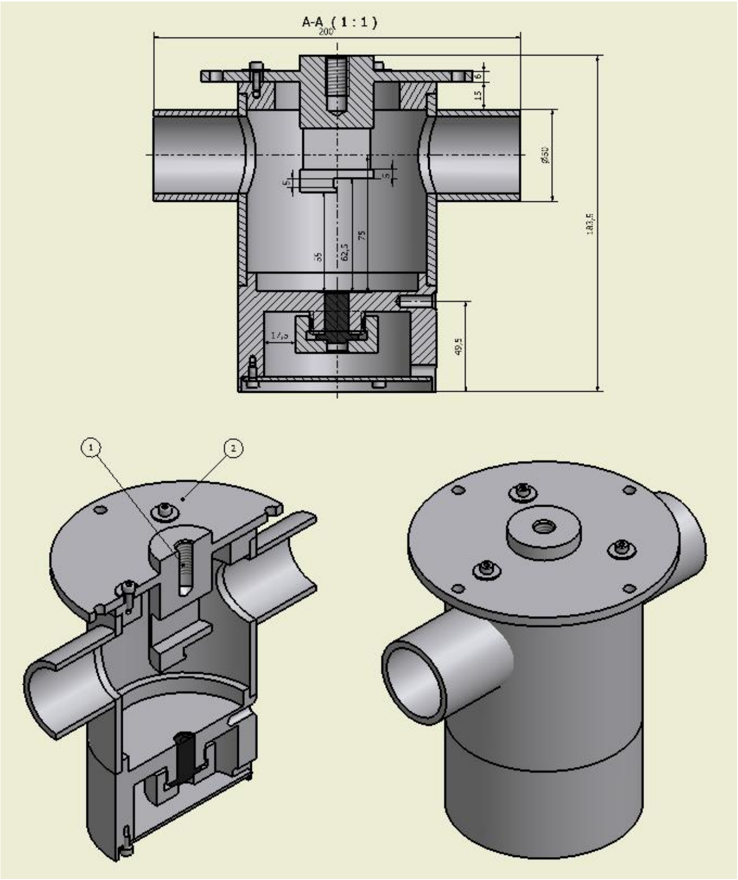
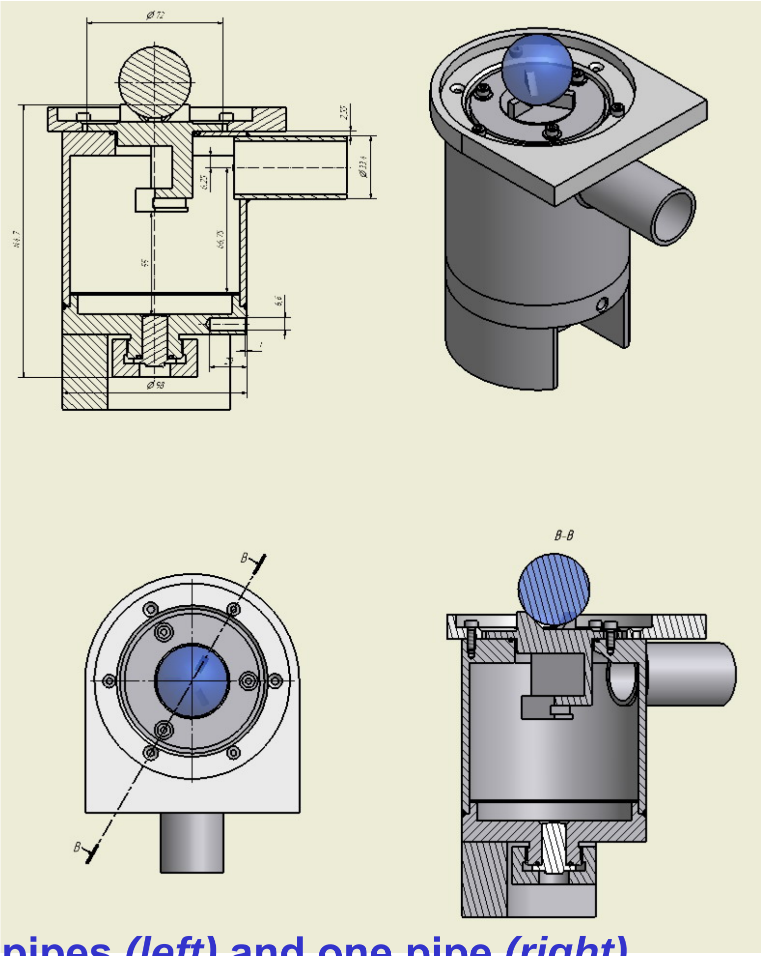
MECHANICAL DESIGN
(one of the versions)

- **Part 1 should be done with invar for best temperature stability of linear sizes.**
- **All another body parts should be done with stainless steel**
- **No electronics inside the body of ULS.**
- **distance to transducer up to 2m**
- **10m - optional**



MECHANICAL DESIGN





ULS design modifications: with two water pipes *(left)* and one pipe *(right)*

6. TEST RESULTS

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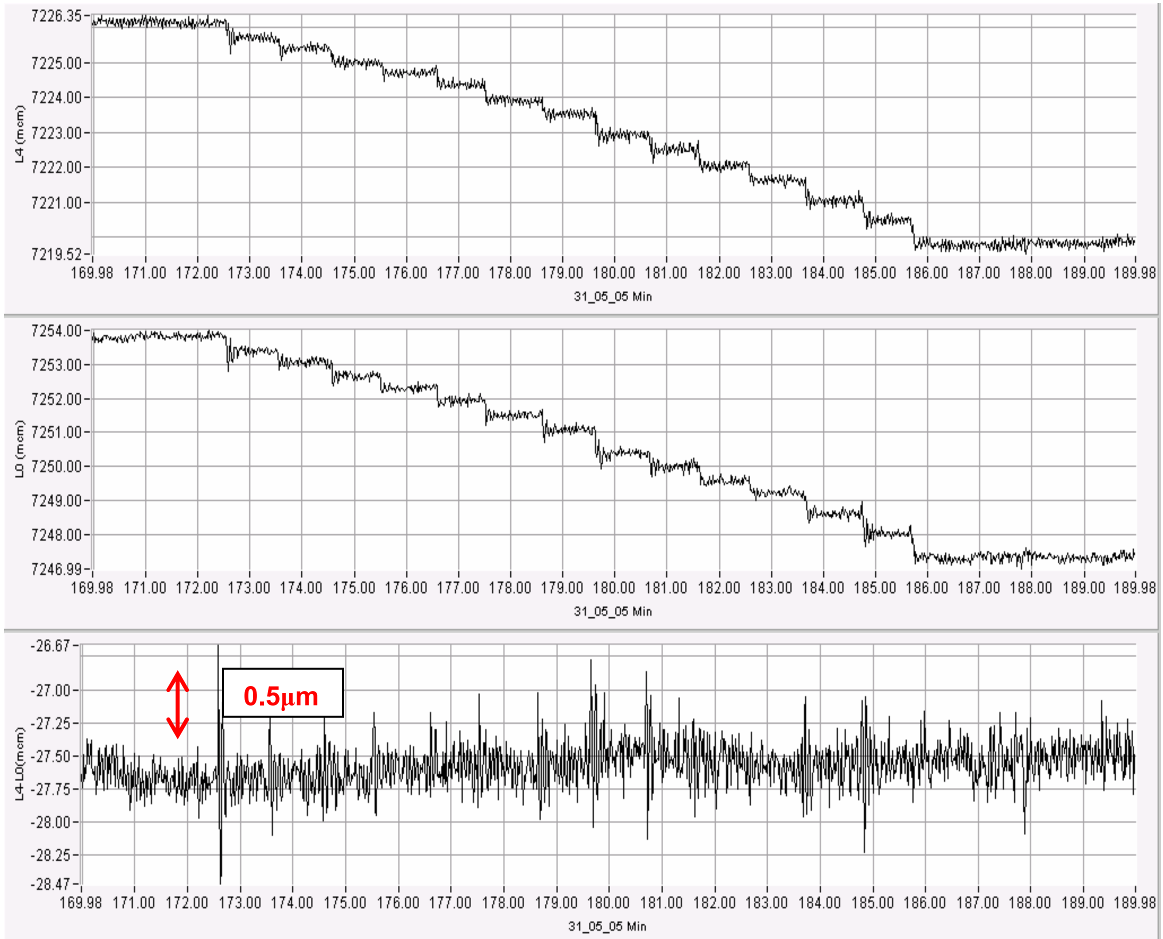

Level steps => 0.5μm

Peak – to – peak error 0.3μm for each Sensor
(0.5μm for both)

It corresponds to
r.m.s. value about 0.1μm for each ULS
of this 15-minutes run.

(***Excluding the short splashes***
due to transient process produced by water drops)

Test of the ULS sensitivity (water drops test)

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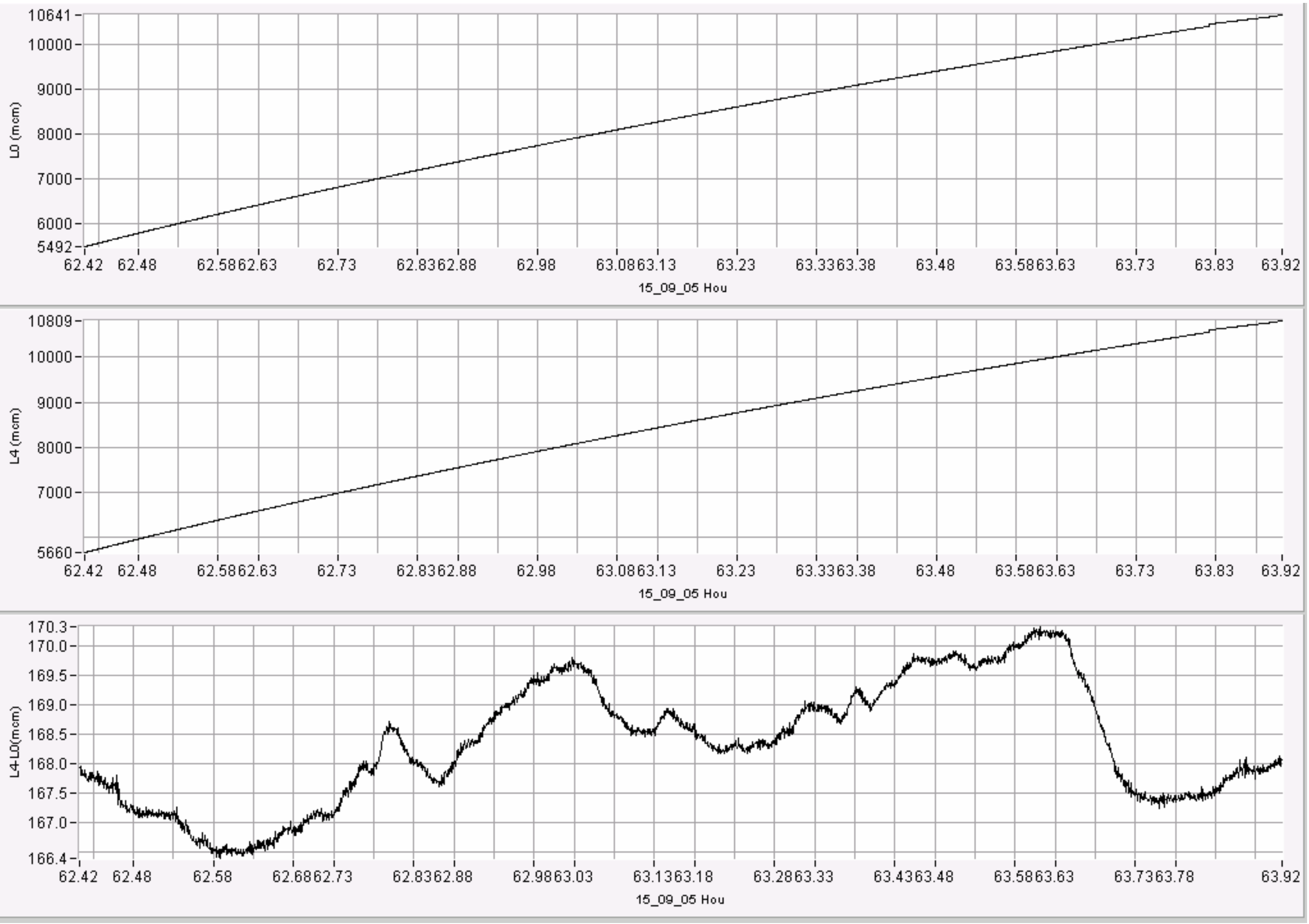

Absolute level increases

More then

5mm

Level difference

Less than

4µm

Checking of the accuracy (water flew in)

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Test stand with SAS and ULS at SLAC. June 2006

7. REFERENCES

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Welcome to Siberia