



GPS DISCIPLINED OSCILLATOR (FREQUENCY STANDARD) 10,000,000,000x MHz

Tasks

1. According to the presented wiring diagram, design and printed circuit board motif .
2. Transfer the designed printed circuit motif to the printed circuit board .
3. Production the printed circuit board .
4. Assemble the board .
5. Test and commission the completed device.

Introduction

In the practical part, you will build an extremely accurate and stable oscillator with a frequency of 10 MHz. For a home or school laboratory, you will get a frequency standard with atomic clock accuracy.

You have at your disposal double-sided printed circuit boards coated with a photosensitive layer of size 100x160 mm. The exact size of your PCB design is not given, use as much of the material as you need.

The schematic files for the Eagle design system can be downloaded from <http://www.cern.ch/zenit>

Name the finished project with your competition number (e.g. A01.brd, A01.sch) and upload it to the repository (by clicking on the link in the pdf entry).

The use of an autorouter, as well as any external help, is prohibited at the competition. Violation of the regulation will be penalized by disqualification.

Constructions from ZENIT are very popular with students, for example, as practical exams. We would like to inform you that this is a copyrighted work and that any part of it can be used in your graduation thesis or other work, and you must have the consent of the authors (contact at the end of the document) and the work must be correctly cited with the full reference of the source.

Grading

A maximum of 80 points can be obtained for the practical part. The evaluation of the practical part is as follows:

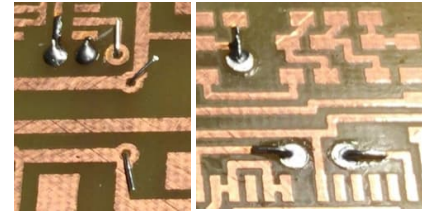
- Printed board design maximum 20 points
- Soldering quality maximum 15 points
- Cleanness of execution maximum 5 points
- Functionality of finished device maximum 40 points, of which (category B/category A):
 - Oscillator block 10/15 points
 - Thermostat 10/10 points
 - Phase detector and phase locked loop 10/10 points
 - Microcontroller , indicators , GPS module 10/5 points

The overall quality of the board design (layout of components, electrical quality of the board, motif design, number and placement of jumpers, overall size of the board...) is evaluated under the "PCB Design " parameter .

Notes on printed circuit board design

You are designing a printed circuit board for a high-frequency circuit. Design quality is critical to circuit functionality. Use short and direct connections. Place the parts close to each other.

The entire bottom of the board is the ground plane, draw a polygon in the Bottom layer and name it GND. The connection to the ground is realized by jumpers. If the GND signal wire is to be longer than 10-15 mm, use a ground plane grommet. The recommended method of transition between the layers of the double-sided board is a "metalled" hole (in Eagle Via), drill diameter 0.6-0.8 mm, surface diameter min. 2.2 mm. A short wire is inserted into the hole from both sides, fixed and soldered, see photographs.



Carefully read the following instructions, they have a direct impact on your success and point evaluation:

- **The use of autorouter is prohibited. Violation of the regulation will be penalized by disqualification.**
- **Save the PCB design at regular intervals.**
- **Do not use polygons on the component side**
- **All components and wire jumpers must be mounted on the PCB component side.**
- Use a grid of 0.635 mm
- Use the entire lower side of the double-sided board as ground (GND)
- In order to correctly attach the film to the board, always place a long enough legible text in the design. We recommend "COMPONENTS PAGE" to the TOP layer. This text must also be legible on the attached foil.
- Parts and connections must be placed on the same layer, otherwise they will not be connected, or will be mirrored (...in Eagle they must be the same color)
- The recommended width of the joint and gap is min. 0.6 mm. Very short connections of 0.4 mm can also be made

Device testing and submission to the committee

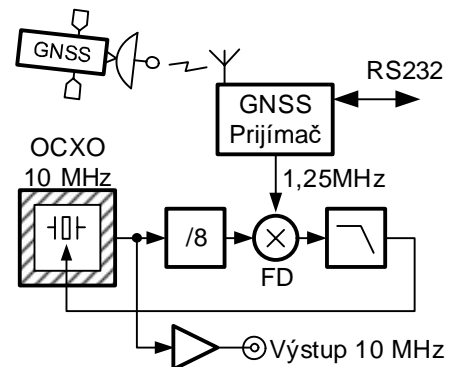
Competitors have at their disposal a revival workplace where they can test their product before submission. Problems that competitors find and correct before the official handover of the product are not included in the evaluation. Problems that are detected during the official submission to the evaluation committee are included in the final evaluation.

The connection is designed in a modular way, and the individual blocks can be revived separately. In case of time constraints, you do not need to design or install a complete circuit board. It will be possible to revive the product in parts. The competitor will still be awarded points for completed and functional work according to the degree of development.

Theory of operation

For some applications, it is necessary to have signals with a very precisely known frequency, or vice versa, if we want to measure the frequency of an unknown signal, we need an exact reference with which the unknown signal is compared. We can only maintain the frequency of common RC or LC oscillators at the percentage level (10^{-2}), which is not very useful for measurement applications. Better parameters are achieved by crystal oscillators (10^{-5} - 10^{-7}), the best quality thermostated crystal oscillators are stable and accurate at the level of 10^{-10} . If our application requires even higher stability, we need to switch to atomic clocks. Currently, the most stable atomic clocks are implemented by the active hydrogen maser (10^{-14}) and the Cesium fountain (10^{-15}). There are only a few such stable oscillators on the whole planet and they are extremely expensive. However, thanks to the massive development of satellite positioning systems (GNSS - global navigation satellite system, i.e. GPS, Galileo, GLONASS, BeiDou), we have the exact frequency and exact time literally at our fingertips. Complete receivers of navigation signals are no bigger than an integrated circuit, cost units to tens of Euros and are commonly available.

A way to generate a high-quality signal with a precise frequency without having an atomic clock is to connect a high-quality and highly stable crystal oscillator to a GNSS receiver. The crystal oscillator will generate a high-quality signal with a stable frequency,



but we do not know its exact absolute value. The satellite signal receiver, on the other hand, generates a precisely known frequency, but the quality of the signal is not high.

Using the so-called phase lock loop (PLL) we can filter out the imperfections of the GNSS signal and control the oscillator frequency so that it has an exact value of 10,000,000,00x MHz. If we design and use an extremely high-quality and stable crystal oscillator (which is our case), it will even be enough if we only "discipline" the oscillator, ie control its frequency very freely, so that its value is accurate. The block diagram of the circuit is in the inset image.

The basis of the construction is a voltage-controlled, thermostated crystal oscillator (OCXO) in the Colpitts topology. Thanks to the sponsor, we can use the highest quality type of crystal that currently exists, the so-called SC cut. We operate the crystal on the third harmonic. But the oscillator would oscillate at all frequencies where the oscillation condition is met. Therefore, using the resonant circuit L2-C7 tuned between the first and third harmonics, we must suppress the unwanted oscillations at 3.333 MHz and select 10.000 MHz. The second resonant circuit L1-C6 suppresses the parasitic resonant mode of the SC-type crystal, whose frequency is only 9% above the nominal one. Both resonant circuits must be tuned precisely, otherwise the oscillator will not oscillate, or will not be tuned to the correct frequency due to too high a capacitive load on the crystal.

The resonant frequency of the oscillator can be fine-tuned in the range of approx. 2 ppm (20 Hz) using varicaps D1/D2. Pin bar CON1 is used for oscillator testing. If the potentiometer is connected between pins 1-3-5, the frequency can be tuned manually (for example, to measure the range of the oscillator), if the jumper is connected between pins 3-4, the oscillator will work in a closed loop of the phase delay.

The SC-type crystal has a region of zero frequency temperature coefficient significantly wider than cheap types of crystals (eg AT-rez, BT-rez). The disadvantage is that this temperature is approximately 90°C. Therefore, a thermostat is part of the design, which heats the crystal and keeps it at a constant temperature.

A power transistor T1, which serves as a heating element, is attached to the crystal using a heat-conducting material. The temperature of the crystal and the transistor is sensed by the thermistor R10. All three parts are connected using heat-conducting material and fixed with several layers of heat-shrink tubing. In the design of the circuit board, you must respect the mutual position so that the assembly can be soldered. The grip points (centers) of XTAL1 and T1 must be exactly 5.08 mm apart. The soldering pads for the R10 thermistor must not be further than 15 mm from the center of the assembly, but the exact position is not important. The layout is shown in the image to the right.

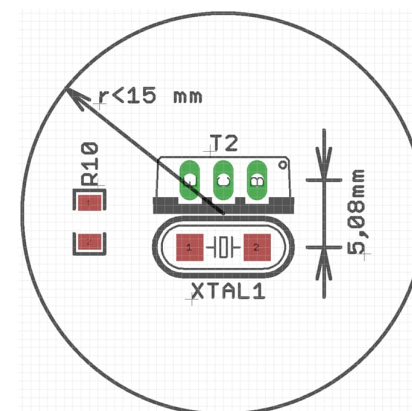
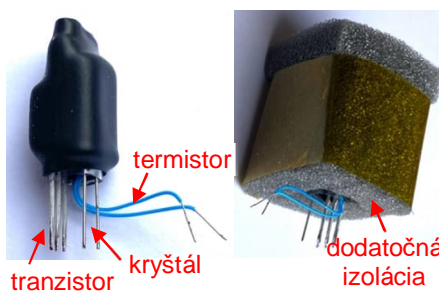
In order to achieve better thermal insulation, it is advisable to put additional foam insulation on this sandwich.

The temperature is regulated by a proportional-integral (PI) regulator, which forms the thermistor R10, the reference resistor R23+R24 (it must have the same value as the thermistor heated to a temperature of 90°C), the error amplifier IC6A, which also forms the proportional part of the regulator. The integral part of the regulator consists of IC6B, a non-inverting integrator in the circuit.

When switched on, the heating current is limited by resistor R11 to approximately 550 mA (5 W). Heating to the nominal temperature takes approximately 2 minutes. After reaching the working temperature, the voltage value of the P-branch gradually drops to zero and the voltage value of the I-branch to the steady value necessary to reach the working temperature. The required constant heating power is approximately 2 W.

To achieve the best stability, the oscillator and the temperature controller have their own 5 V voltage stabilizer (IC1). In order to achieve even better stability, it is advisable to build the entire circuit in a closed box, which will prevent the flow of air around the analog circuits of the oscillator and the phase delay.

A precisely known frequency from a GNSS (GPS) receiver is used as a frequency reference, which is placed on a special board outside, with a direct view of the sky. The uBlox SAM-8Q-0-10 receiver is capable of generating any frequency in the range of 1 Hz to 10 MHz with a resolution of 1 Hz linked to the atomic clocks of navigation satellites. In terms of value, too low a frequency is problematic for phase lock (for example, the popular 1 pulse per second) and at the same time a high frequency from the receiver is not optimal from the



point of view of phase noise (signal quality). After tests with high-end instruments, we selected 1.25 MHz as a comparative reference frequency for the phase lock. The GNSS module can generate it with the highest quality and at the same time we can easily create it by binary division of the oscillator frequency by eight (integrated circuit IC3A).

Two reference frequencies of 1.25 MHz are compared in phase-frequency detector IC5A. The output of the detector is pulses, the mean value of which, very simply put, corresponds to the difference in frequency between the compared sources, i.e. the precisely known frequency from the GPS and our oscillator. This error signal is corrected by the low-pass filter IC4a and tunes the frequency of the crystal oscillator so that it is exactly the same as the reference frequency from the GPS. For more advanced students - the phase loop is of the second type and the second order, so it can fully compensate for both the phase error and the constant frequency error. In order to achieve the best quality of the output signal, the frequency response of the filter can be narrowed down to 1 Hz by increasing the value of C4 and C5 to 100 μ F. However, the adjustment requires a more sophisticated program that ensures initial synchronization with GPS.

The output signal of 10 MHz is "amplified" by the gates of IC2 and fed to the BNC connector. Resistors R3 and R14 set the DC bias for gate IC2A. Each oscillator is individual, for optimal parameters it is advisable to set the bias voltage so that the output signal from IC2A is around 50%. The output of the oscillator can be loaded with an impedance of 50 Ohms. If a sine signal is required, it is necessary to use a low-pass or band-pass filter.

The GNSS receiver is placed on a special small board. The receiver and oscillator are connected by a shielded Ethernet cable.

The circuit is powered by a DC source of 9 V, 1 A. After switching on the device, it takes approximately two minutes for the crystal to reach an operating temperature of 90°C. The GNSS receiver needs approximately 2 to 5 minutes to capture the initial synchronization. After synchronizing to GPS, the phase lock loop corrects the frequency of the crystal oscillator and the output frequency is 10,000,000,00x MHz. The program in the microcontroller sends the status of the device, the exact time and date (in the form *29-12-2021 12:50:17 GPS valid, Temp ok, PLL locked*) via the serial line. If you are not going to use the device as a very accurate frequency source, you can still use it as a very accurate clock. Expand the program according to your own ideas.

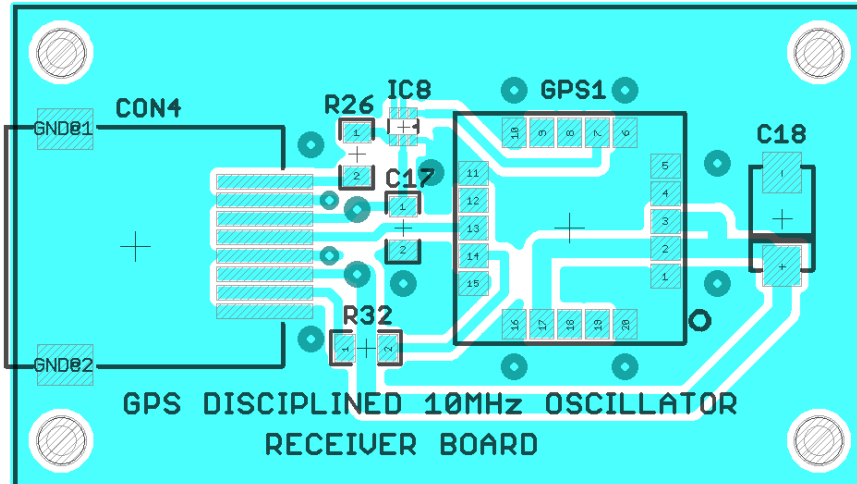
GNSS receiver module

uBlox SAM-M8Q GNSS receiver enables signal reception of three satellite systems: European Galileo, American GPS and Russian GLONASS. The program is set to synchronize to any of the systems.

The receiver is produced in a case, which is very difficult to install by hand. That's why we decided that you will get a ready-made, professionally made printed circuit board for the GNSS receiver module. As part of the professional seminar, you will learn how to insert printed circuit boards with a template. You will immediately practice the knowledge gained - using a template, you will apply tin paste to the printed circuit board, install the components and remelt the printed circuit board in the oven.

The receiver should have a direct view of the sky. The receiver can also be placed behind a window, but make sure that your windows are not metallized (due to the shielding of infrared radiation). Such windows have a high attenuation for radio waves, the receiver will not synchronize at all, or will have frequent outages. We recommend installation in a waterproof plastic installation box.

Installation plan of the receiver board:



Bonus: clock display

As a souvenir, we have prepared accessories for the oscillator - a display on which you can display the date and time, or other information from the GNSS receiver. If you use an oscillator, connect the display to your board with data wires. If you only want to use the clock, install a small microcontroller board and connect it directly to the display board with a pin strip.

The program in the microcontroller already contains a part operating this display, just connect it. If you want, edit it to your liking and send us a photo of what you have created.

Unfortunately, we did not have the opportunity to test the printed circuit boards before sending them to production. There are two small mistakes on them that you can easily fix. They are marked in red in the diagram.

The display driver has an open type output drain, so that the MOSFET transistors driving the common anodes are closed, it is necessary to add a resistor between G and +5V. The serial line from the GNSS module is fed to the proper UART input Rx, not the input for the software serial port.





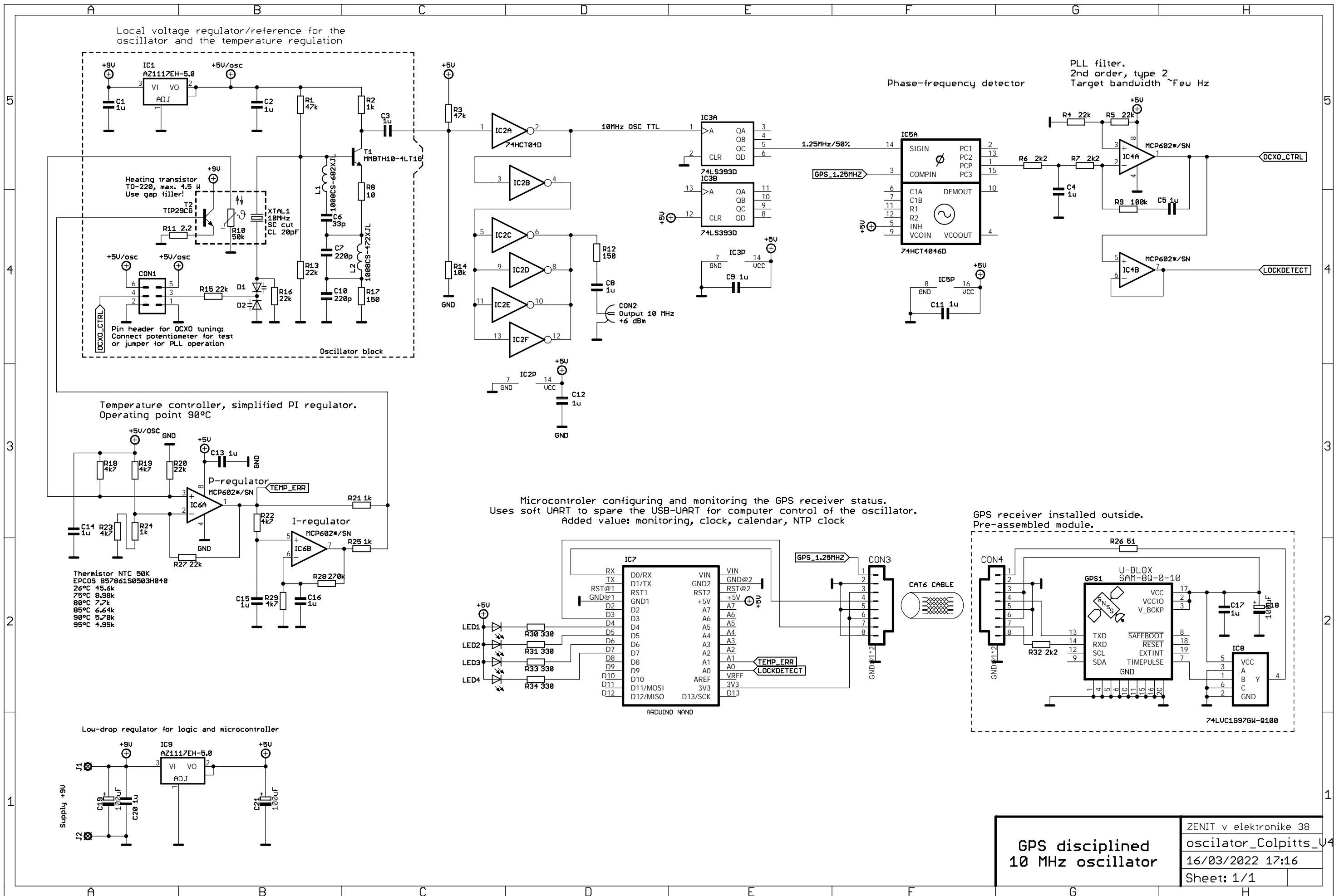
Parts list

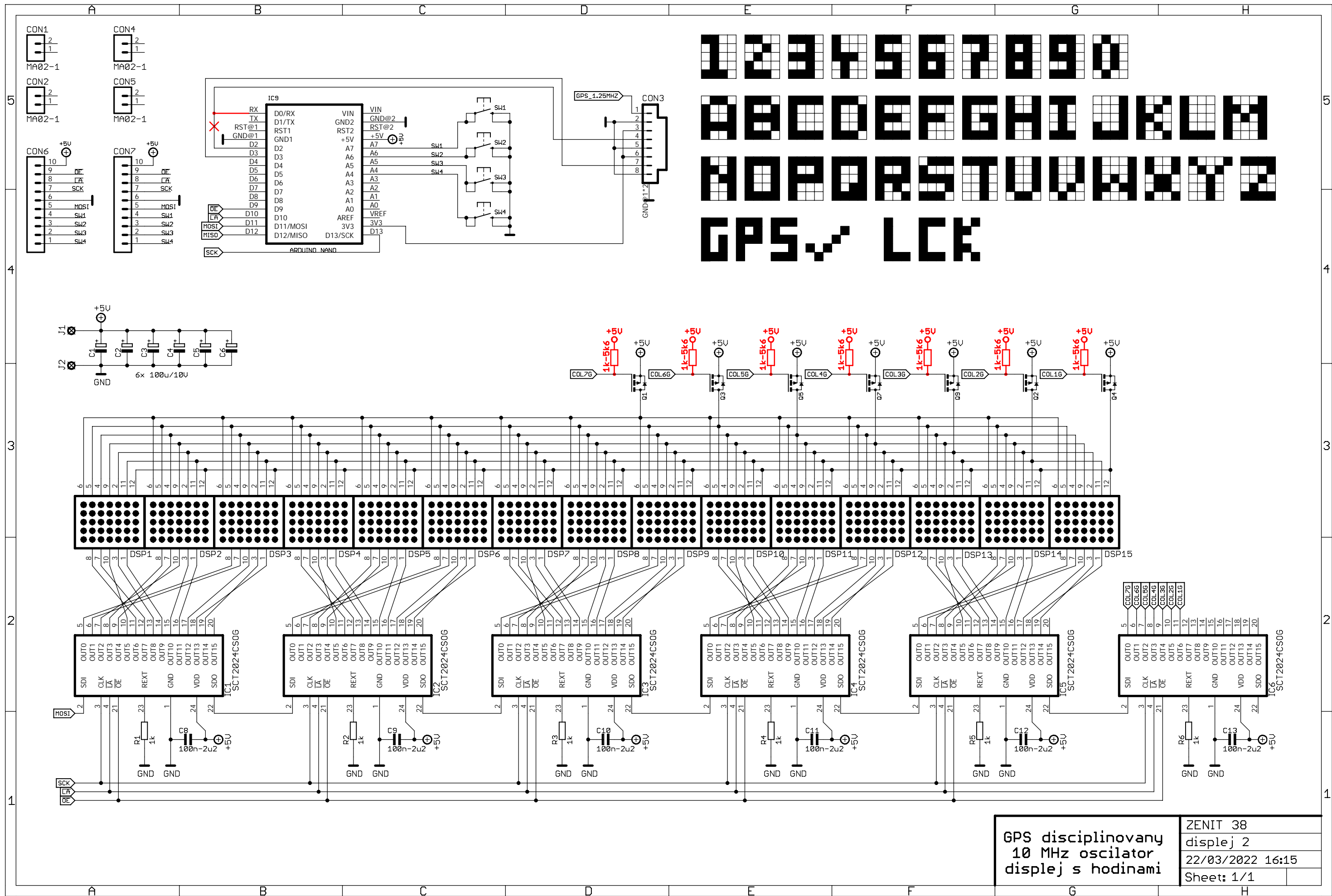
Parts	Value	Note
C1, C2, C3, C4, C5, C8, C9, C11, C12, C13, C14, C15, C16, C17, C20	1 u	capacitor 1206
C18, C19, C21	100uF	Tantalum , size E
C6	33p ±5pF	capacitor 1206, a must accurate fine-tuning
C7	220 p	capacitor 1206
C10	100 p	capacitor 1206 (change 31.3.2022)
CON1	Pin. Bar 3x2	
CON2	BNC connector	drill , solder to the Top page boards
CON3, CON4	RJ45 connector	
D1, D2	BB640	Varicap 69pF@1V, 33pF@5V
GPS1	SAM-8Q-0-10	GNSS receiver , u - Blox M8 with integrated antenna
IC1, IC9	AZ1117EH-5.0	Stabilizer with low decrease voltage
IC2	74HCT04D	
IC3	74HCT393D	Dual 4-bit decade and binary COUNTER
IC4, IC6	MCP602*/SN	
IC5	74HCT4046D	Phased curtain with VCO
IC7	Arduino Nano	drill , solder to the Top page boards
IC8	74LVC1G97GW-Q100	Multifunctional gate
L1	1008LS-682XJL	Inductance 6.8uH, Coilcraft
L2	1008LS-472XJL	Inductance 4.7uH, Coilcraft
LED1, LED2, LED3, LED4	LL-S150VC-V1-1B	LED red , 1206
R1, R3	47 k	resistor 1206
R2, R21, R24, R25	1 pc	resistor 1206
R4, R5, R13, R15, R16, R20, R27	22 k	resistor 1206
R6, R7, R32	2k2	resistor 1206
R8	10	resistor 1206
R9	100 k	resistor 1206
R10	B57861S0503H040	Thermistor 50k EPCOS, place next to crystal
R11	2.2	resistor 1206
R12, R17	150	resistor 1206
R14	10 k	resistor 1206
R18, R19, R22, R23, R29	4d7	resistor 1206
R26	51	resistor 1206
R28	270 k	resistor 1206
R30, R31, R33, R34	330	resistor 1206
T1	MMBTH10-4LT1G	VHF/UHF NPN Transistor
T2	TIP29CG	Place next to crystal
XTAL1	10MHz	Crystal 10 MHz, SC-cut, 3rd overtone, CI 20 pF

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GPS disciplinovaný 10 MHz oscilator displej s hodinami	ZENIT 38
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