ELECTRONICS & DEFENSE

MRO-50

User Manual

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1. Introduction

The mRO-50 is a miniaturized Rubidium Oscillator with the dimensions, packaging and pinout of crystal oscillators (OCXO), measuring 50.8 mm x 50.8 mm x 19.5 mm. It delivers a square reference signal at 10 MHz (0 to 3.3 V) with outstanding performances for a steady power consumption below 0.45 W at room temperature.

Such frequency references are well suited for applications demanding low power consumption, accuracy and retrace, high frequency stability and low frequency drift such as telecom and mobile network synchronization (TDM, PTP), oil and gas sensor-based exploration, navigation or timing instruments.

The mRO is described in this document divided into 4 chapters:

- A brief introduction
- A simple description of the principle of the clock
- The specifications of the system
- The operation manual

2. mRO system description

2.1 Principle of operation and basic configuration

The mRO is a miniature rubidium clock and essentially consists of a voltage-controlled crystal oscillator (VCXO) which is locked to a highly stable atomic transition in the ground state of the 85Rb isotope. While the frequency of the VCXO is at the convenient standard frequency of 10 MHz, the rubidium clock frequency is at 3.036 GHz in the microwave range. The microwave signal is directly generated with a second voltage-controlled oscillator (VCO). The phase-stable link between the two oscillators is established with a fractional-N PLL (phase-locked loop).

The rubidium atoms are confined in a vapor cell at an elevated temperature. The cell is placed inside a cylinder with a gap to which the microwave power derived from the VCO is coupled. The 85Rb atoms in the cell occur with equal probability in the two hyperfine energy levels of the ground state 5S (F=2 and F=3).

In order to detect the clock transition between these two levels, the atoms need to be manipulated in such a way that most of them occur in only one level. This is done by optical pumping via a higher lying state (5P). Figure 1 shows the atomic energy levels and transitions involved in the optical pumping process on the D1-line at 795 nm.

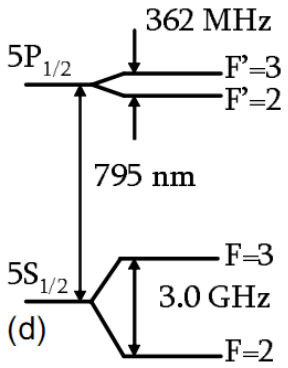

Figure 1: 85Rb optical pumping (D1 line)

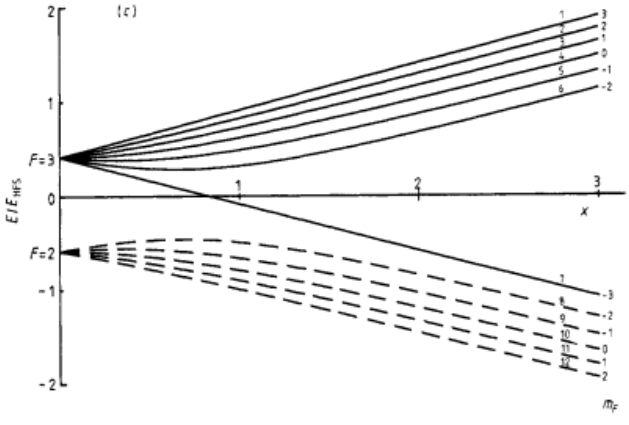

Figure 2: The C-field (static magnetic field) splits the Zeeman levels of the 85Rb hyperfine ground-state 5S. The clock transition between the mF = 0 levels is only second-order sensitive to the applied magnetic field.

The pump light comes from a VCSEL (Vertical Cavity Surface Emitting Laser) which is tuned to resonance with the transition between the ground-state F=3 level and the (un-resolved) excited states F'=2,3. The pump light excites 85Rb atoms which are in the upper hyperfine level (F=3) to the short-lived excited state 5P from which they decay to the two ground state levels (F=2,3) with equal probability. Since pumping occurs continuously out of the F=3 level, a steady-state is reached where most atoms are found in the F=2 level.

The level of the transmitted pump light is detected by a photodiode after the cell. When a microwave field resonant with the clock transition F=2*F=3 is coupled to the interaction region, the level F=3 is repopulated and light absorption is enhanced. A sweep of the microwave field over the resonance is detected as a small dip in the transmitted light level after the cell.

This signal from the photodiode is fed into a synchronous detector whose output generates an error signal which corrects the frequency of the crystal oscillator so that the (fixed) phase-locked loop keeps the microwave VCO exactly on the atomic resonance maximum.

The vapour cell is filled with metallic rubidium that contains both isotopes 85Rb (72%) and 87Rb (28%). In addition the cell is filled with a buffer gas which collides with rubidium atoms so as to keep them away from the cell walls and restrict their movement. As a result the rubidium atoms are practically "frozen in place" for the interaction time with the microwave field. In this way the Doppler-effect is essentially removed and a narrow line width results.

The cell region is also surrounded by a pair of C-field coils which generate a small axial static magnetic field to resolve the Zeeman sub-transitions of the hyperfine line and select the clock transition, i.e. the one with the least magnetic sensitivity, see Figure 2. To further reduce the magnetic sensitivity, the complete physics package is placed inside a magnetic shield.

Figure 3 gives a basic overview of the different functional blocks of the rubidium atomic clock. The rubidium clock consists of two different packages. First, the Physics Package noted PP, which includes the VCSEL, the rubidium vapor cell, the cylinder coupling the microwave to the rubidium atoms, two C-field coils and an optical filter. Second, the Electronics Package noted EP, which includes the microwave generation, the detection circuitry, temperature controllers, monitoring and signal processing.

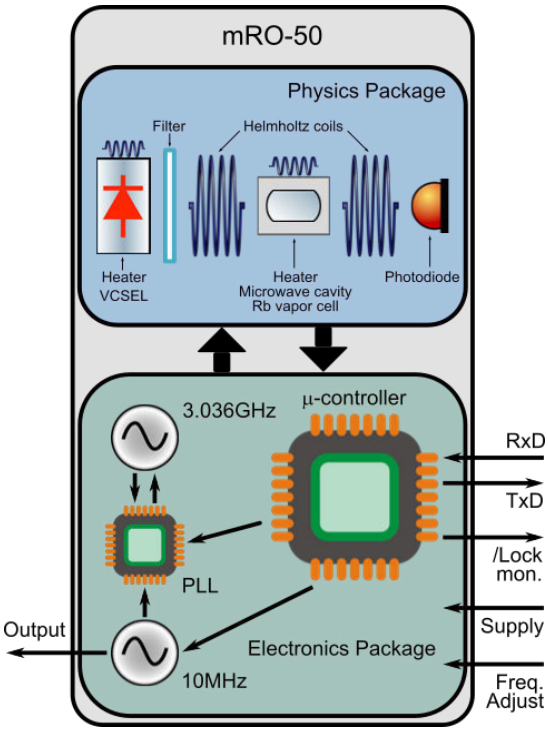

Figure 3: miniaturized Rubidium atomic clock principal block diagram

2.2 Physics Package (patented)

The main design characteristics of the PP are its low power consumption, small size and mass, along with minimal environmental sensitivities and mechanical ruggedness.

All parts of the PP are incorporated into a DIL-14 package hermetically sealed off under Xenon atmosphere to reduce temperature exchange by convection and minimize electrical power consumption.

The light source selected for its compactness and low power consumption is a Vertical Cavity Surface Emitting Laser (VCSEL) at 795 nm. It is coupled to a glass blown cell filled with Rubidium and buffer gas surrounded by a cavity coupled to the microwave signal.

The cavity has two purposes: 1) couple the Rubidium atoms to the microwave field as mentioned previously but also 2) transfer the heat to the cell and make a thermally stable environment around the glass cell as an oven. Both components, VCSEL and Cell, are temperature stabilized.

The design is completed with Helmholtz coils, an optical filter and the photodetector.

2.3 Electronics Package

2.3.1 Atomic resonance signal capture

The mRO transition is a microwave transition at 3.036 GHz.

The microwave resonance which occurs as a dip in the optical signal after transiting the cell, is detected by a photodiode.

The basic purpose of the EP is to synchronize the entering microwave frequency, derived from a temperature compensated crystal oscillator (TCXO), to this absorption dip. It is achieved by tuning the microwave frequency to maximum optical absorption.

Frequency variations of the microwave signal are transformed into DC current changes at the photodetector. The dip, visualized in the photocurrent versus microwave frequency curve of Figure 4 is very small: on the order of 1% of the total photocurrent.

Since DC detection of the dip is not feasible, an AC detection method is used for the following reasons:

- The dip amplitude is very small compared to the total photocurrent.
- The slope of the derivative of the dip photocurrent versus microwave frequency corresponds to roughly 100 pA/Hz. AC detection is the only solution to have a good signal/noise ratio since the photo-detector with associated amplifier are affected by flicker noise.

The AC method involves square wave frequency modulation of the microwave signal at a rate of approximately 105 Hz. As shown in Figure 4, the modulated microwave frequency flips between 2 discrete frequency values f1 and f2. The resulting photo-current i(t) appears also (after the transient) at 2 discrete values i1 and i2. The difference between i1 and i2 produces the error signal used to adjust the crystal oscillator center frequency until the mean value of f1 and f2 is exactly equal to the rubidium hyperfine frequency.

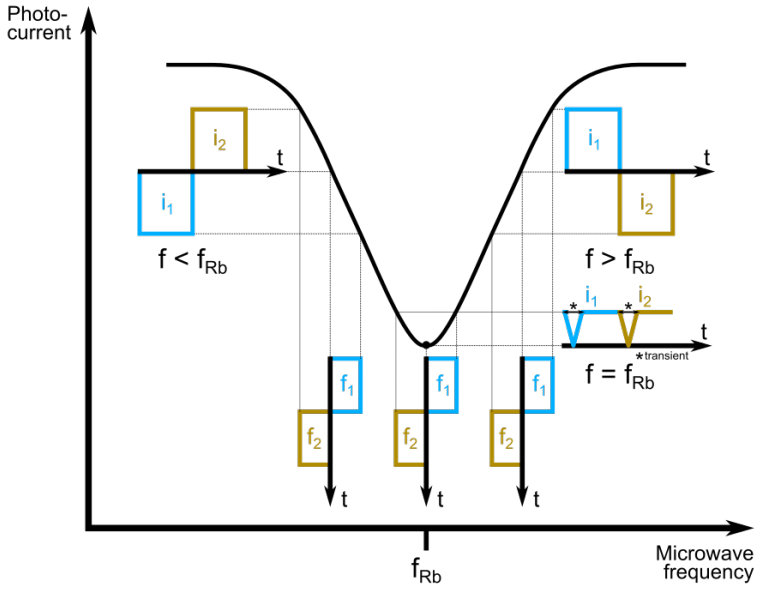

Figure 4: Atomic resonance: error signal detection

2.3.2 Temperature controllers

Since the temperature of the VCSEL and the Cell must be adjusted independently, two separated heaters are necessary to control the temperature of the PP main parts. The temperatures are controlled by compensating thermal losses using heating elements (no cooling). Temperature regulation servo-loops are based on a temperature sensor (NTC within a Wheatstone bridge), Proportional-Integral (PI) regulator and a heating element.

2.3.3 C-field

A pair of C-field coils inside the PP generate a magnetic field which separates the rubidium spectral lines. This magnetic field allows fine-tuning of the output frequency by shifting the rubidium resonance frequency by the second-order Zeeman effect.

A stabilized current drives the coils. The current is adjustable for fine-tuning of the output frequency and can be set by a software interface or by an analog voltage applied to the mRO pin #1.

2.3.4 Telemetries

The user can access these data from a software GUI shown in Figure 5. Telemetry parameters shown include:

- Error signal of the atomic lock loop
- DC signal on photodiode
- VCSEL temperature
- Control signal of the VCSEL temperature controller
- Cell temperature
- Control signal of the Cell temperature controller
- EP temperature
- VCSEL driving current
- Voltage across the VCSEL
- Control voltage of the 10 MHz crystal

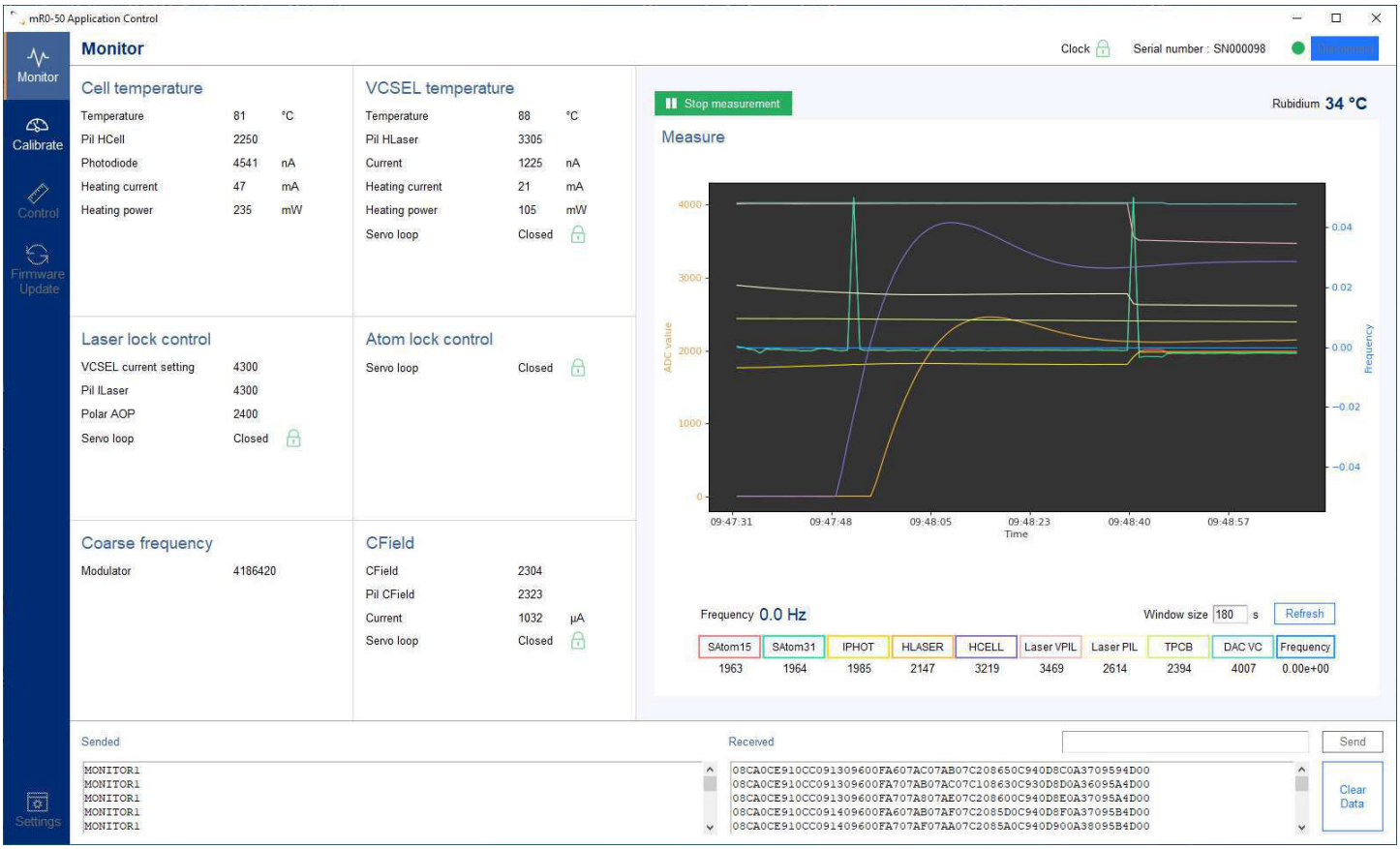

Figure 5: Control and monitoring software for the mRO-50

More details are given in 4.8.3.
More specific information can be found in the mRO-50 - Evaluation Kit document

2.3.5 Frequency adjustment

The C-field coil within the PP provides fine frequency adjustment capabilities. The value of the output frequency is settable by applying an analog voltage to pin #1 (see 4.8.4) or by software.

3. The mRO-50 SPECIFICATIONS

The specifications of this product are available on our website, safran-navigation-timing.com.

4. mRO-50 installation and operation

4.1 Introduction

This chapter of the manual contains information regarding the installation and operation of the mRO-50. It is recommended to read this chapter carefully prior to operating the unit.

4.2 Safety!

- Use proper ESD precautions

- Ensure that all cables are properly connected

- The equipment contains small quantities of rubidium metal hermetically sealed inside the glass lamp and cell assemblies, hence, any dangers arising from ionizing radiation are caused for human health (exemption set in article 3 to Council directive 96/29/Euratom).
- For further information, ask for the «rubidium product data sheet».
- Handling the product in a reasonably foreseeable conditions do not cause any risk for human health, exposure to the SVHC (substances of very high concern) would require grinding the component up.

4.3 Environmental Responsibility

- The equipment contains materials, which can be either re-used or recycled.
- Do not deposit the equipment as unsorted municipal waste. Leave it at an authorized local WEEE collection point or return to Safran Trusted 4D to ensure proper disposal.
- To return the appliance:
  - Submit a support ticket at aftersales.clocks@nav-timing.safrangroup.com and request an RMA.
  - We will contact you for more information and/or with shipment process details.

4.4 Shipping and receiving information

The mRO-50 is packaged and shipped in a foam-lined box. The unit is inspected mechanically and electrically prior to shipment. Upon receipt of the unit, a thorough inspection should be made to ensure that no damage has occurred during shipping. If any damage is discovered, please contact:

SAFRAN TIMING TECHNOLOGIES SA

PHONE: +41 32 732 16 66

CH-2000 NEUCHATEL / SWITZERLAND

Should it be necessary to ship the unit back, the original case and packing should be used. If the original case is not available, a suitable container with foam-packing is recommended.

CAUTION

Care must be taken for the transportation of the mRO-50 to ensure that the maximum acceleration due to a shocks 50g/11ms is not exceeded.

mRO-50 contains glass bulbs, crystal resonators.

When mRO-50 integrated into an instrument, such instrument shall be packed in a suitable container, similar to containers generally use for the transportation of instruments like scope, video display or computer.

4.5 Mounting

CAUTION

Care must be taken to ensure that the maximum operating temperature is not exceeded, (+60°C (+65°C if option E) as measured at the unit's base plate)

This maximum temperature can be reached when operating the unit into forced air flow at 60°C (65°C).

The mRO-50 is a well shielded unit, using several magnetic shield. Nevertheless, some consideration must be given to the operating location of the unit, regardless of its application. To minimize frequency offsets and/or non-harmonic distortion, the unit should not be installed near equipment generating strong magnetic fields such as generators, transformers, etc...

The general information for the mechanical interface of the mRO-50 unit is provided in Figure 6 (all dimensions in mm [inch]).

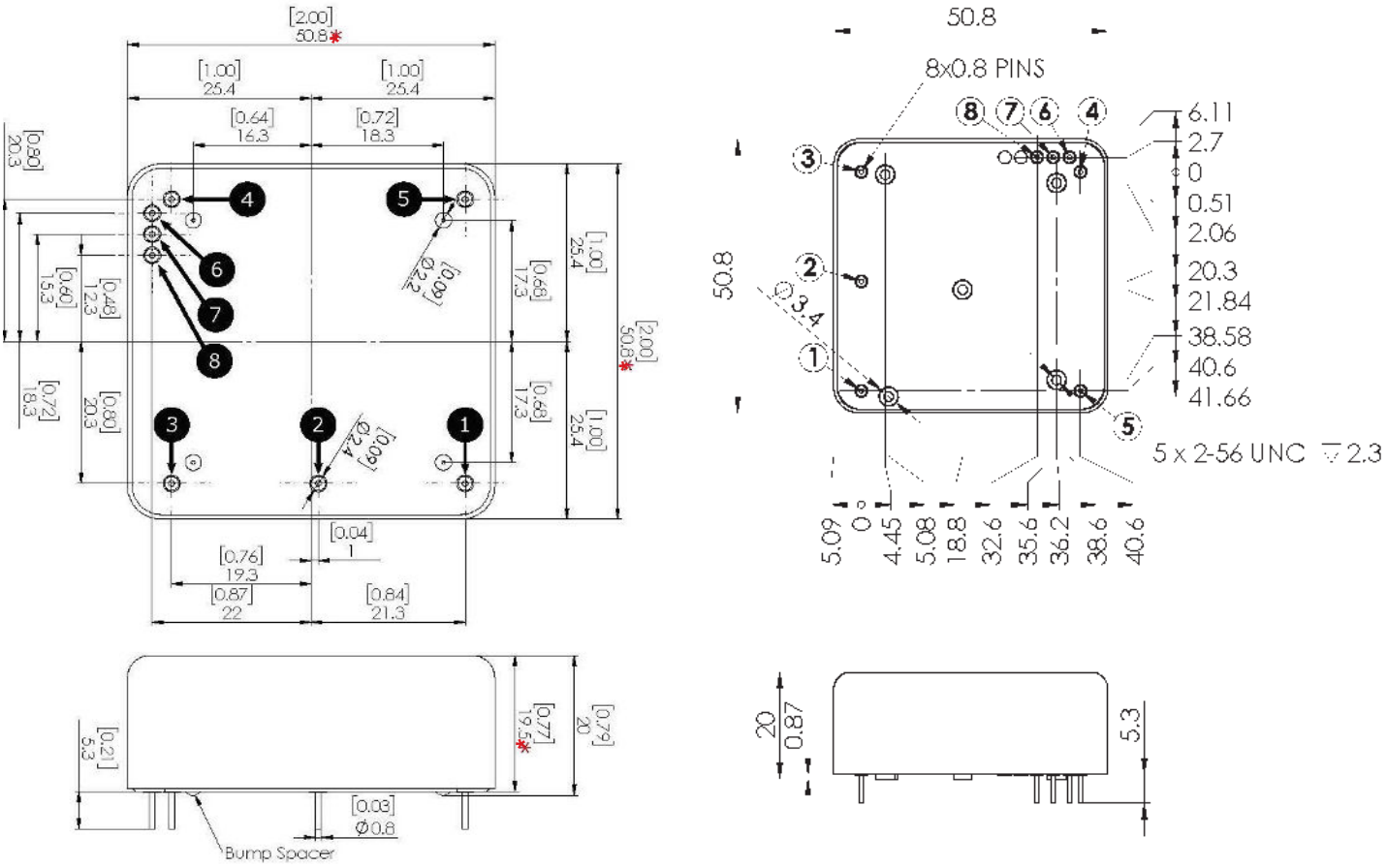

Figure 6: Mechanical interface and dimensions of the standard mRO-50 (left) and E80 option (right)

* ± 0.4 mm

All other quotes are ± 0.2 mm

4.6 Pin Layout:

PIN	FUNCTION
1	Frequency Adjust (Analog +1.5V ±1V)
2	GND
3	10MHz square output (0-3V)
4	GND
5	Power 5V or 3.3V depending on model
6	/LOCK (Bit)
7	TxD
8	RxD

4.7 Normal operation

When 5 or 3.3 Vdc, depending on the option, is applied to pin #5 (+), the unit will immediately generate a 10 MHz signal from the crystal oscillator. Within approximately 70 seconds after application of input power, the unit will "lock", i.e. the crystal is now synchronised by the atomic resonant frequency.

The unit is able to provide a single signal called '/lock monitor' (pin #6) which toggles from high to low level when the internal crystal oscillator is locked to the Rb atomic resonance (see 4.9). The center frequency is tunable by applying an ultra-stable analog voltage to pin #1. It is also possible to adjust the frequency by software (cf. iSource_mRO-50_EvalBoard_Manual.pdf or see 4.8.4).

4.8 Serial interface operation

4.8.1 Introduction

The mRO-50 integrates a micro-controller with A/D and D/A embedded converters. The micro-controller is used to set the parameters of the clock but also to lock the TCXO on the Rb absorption 'dip'.

The built-in serial interface allows an automatic parameter adjustment during the manufacturing process as well as a fine and coarse adjustment of the center frequency. All the working parameters are stored in a built-in EEPROM memory and are accessible through the serial interface for monitoring.

The user must send commands with the following pattern (TxD):

command | carriage return to validate command

Example: monitor1<CR> or MON_tpcb PIL_cfield 0F60<CR>

Remark: the system removes the line feeds and spaces and is case insensitive.

The returned response is decomposed as following (RxD):

response (if there is) + carriage return + line feed

Example: 0123<CRLF>

or error response (if there is) + " ?" + 8 bits number corresponding to the error type + carriage return + line feed

Example: 0123 ?08<CRLF>

4.8.2 Serial interface connection

The data transfer from the mRO-50 is made by direct connection to a PC or standard terminal.

The data transfer parameters are the following:

- bit rate: 9600 bits/s
- parity: none
- start bit: 1
- data bits: 8
- stop bit: 1

IMPORTANT NOTE

In most cases, the serial PC interface accepts the 0 to 3.3V level and a direct connection can be made.

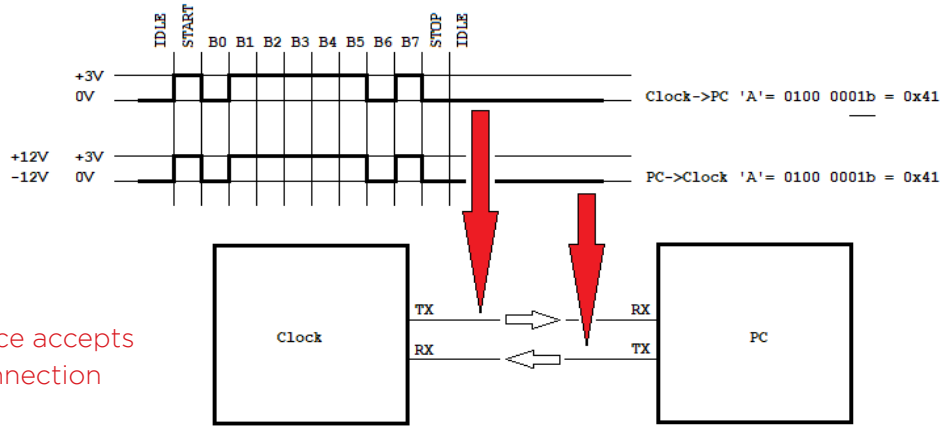

Figure 7: Communication polarity of the mRO-50

4.8.3 mRO-50 parameters monitoring

The parameters monitoring is readable through the serial interface and with the use of the single command 'MONITOR1' followed by a carriage return character. The mRO-50 will respond to this command with an ASCII/HEX coded string as shown below.

AAAABBBBCCCCDDDDEEEEFFFFGGGGHHHHIIIIJJJJKKKKLLLLMMMMNNNNOOOO<CRLF>

(example: 08F90BCE10CC0F8C09600BFC07E207E507C00B5F0D970D1B09D709554D05<CRLF>)

This string is composed of the 15 parameters. The DEC(X) function is the conversion of the hexadecimal to decimal value. Each returned byte is an ASCII coded hexadecimal value. The value are coded full range (4800: 0x0000 to 0x12C0 and 4095: 0x0000 to 0x0FFF) but are truncated into the software of the mRO.

- **(AAAA) Rubidium cell temperature setpoint:** during the optimization of the clock, the temperature of the glass cell is adjusted to maximize the ratio absorption and power consumption. The temperature at this maximum is define as setpoint.

$$R_{NTC}(\text{Ohm}) = \frac{10\,000 \times X}{1\text{-}X} \text{ with } X = 1 - \frac{\text{DEC(AAAA)}}{4800}$$

$$T\,(°C) = \frac{4100 \times 298.15}{298.15 \times \ln(10^{-5} \times R_{NTC}) + 4100} - 273.14$$

  The highest hexadecimal value is 0x0B86 which corresponds to 101°C.

- **(BBBB) LASER temperature setpoint:** the temperature of the VCSEL is set to match the laser wavelength to the Rubidium resonance for a fixed driving current. The temperature determined during this process is fixed as setpoint.

$$R_{NTC}(\text{Ohm}) = \frac{20\,000 \times X}{1\text{-}X} \text{ with } X = 1 - \frac{\text{DEC(BBBB)}}{4800}$$

$$T(°C) = \frac{4100 \times 298.15}{298.15 \times \ln(10^{-5} \times R_{NTC}) + 4100} - 273.15$$

  The highest hexadecimal value is 0x0E49 which corresponds to 100°C.

- **(CCCC) LASER current setpoint during start-up:** after switch-on, the mRO-50 runs the process of locking the light source to the Rubidium resonance which lasts 70 seconds. During this process, the current driving the VCSEL is fixed to a high value. The light control loop is closed and the current will converge to the value which enables the lock.

$$I(\text{mAmp}) = \left[\frac{3 \times \text{DEC(CCCC)}}{4800}\right] \times \frac{1000}{3 \times 510}$$

  The maximum driving current is 1.8 mAmp (0x1130).

- **(DDDD) C-field current setpoint:** a small current crosses the pair of C-field coils which generate a small axial static magnetic field to resolve the Zeeman sub-transitions of the hyperfine line and select the clock transition.

$$I(\mu\text{Amp}) = \left[\frac{3 \times (4800 - \text{DEC(DDDD)})}{4800}\right] \times \frac{10^6}{510}$$

  The maximum current of the C-field is 5882 µAmp (0x0000).

- **(EEEE) Differential integrator DYNAMIC setting:** after switch-on, the mRO-50 runs the process of locking the light source to the Rubidium maximum absorption which lasts 70 seconds. During this period, a voltage bias is added at the input of the light lock corrector to ensure that the controller will converge to the absorption.

$$\mathrm{V(Volt)} = \frac{3 \times \mathrm{DEC(EEEE)}}{4800}$$

  The voltage range is from 0 to 3 V (0x0000 to 0x12C0).

- **(FFFF) TCXO control voltage:** the control voltage of the local oscillator (TCXO) is corrected in real time to lock its frequency to the Rubidium atomic transition at 3.036GHz.

$$\mathrm{V(Volt)} = \frac{3 \times \mathrm{DEC_{signed}(FFFF)}}{4095}$$

  The TCXO control voltage swing from ±1.5 V (0x0800 to 0x07FF) centered at 1.5 V.

- **(GGGG) Atomic signal monitoring (15th sample):** corresponds to the amplitude of the left interrogation signal (see 2.3.1).

$$\mathrm{V(Volt)} = \frac{3 \times \mathrm{DEC(GGGG)}}{4095}$$

  The voltage range is from 0 to 3 V (0x0000 to 0x0FFF).

- **(HHHH) Atomic signal monitoring (31st sample):** corresponds to the amplitude of the right interrogation signal (see 2.3.1).

$$\mathrm{V(Volt)} = \frac{3 \times \mathrm{DEC(HHHH)}}{4095}$$

  The voltage range is from 0 to 3 V (0x0000 to 0x0FFF).

- **(IIII) Photodetector current:** corresponds to the amplitude of the current at the output of the detector.

$$\mathrm{I(nA)} = \left[1.5 - \frac{3 \times \mathrm{DEC(IIII)}}{4095}\right] \times 100000$$

  The current range is from -15 µAmp to 15 µAmp (0x0FFF to 0x0000).

- **(JJJJ) LASER temperature controller voltage:** is the voltage driving the heater of the VCSEL temperature controller.

$$\mathrm{V(Volt)} = \frac{3 \times \mathrm{DEC(JJJJ)}}{4095}$$

  The voltage range is from 0 to 3 V (0x0000 to 0x0FFF).

- **(KKKK) Rubidium cell temperature controller voltage:** is the voltage driving the heater of the glass cell temperature controller.

$$\mathrm{V(Volt)} = \frac{3 \times \mathrm{DEC(KKKK)}}{4095}$$

  The voltage range is from 0 to 3 V (0x0000hex to 0x0FFF).

- **(LLLL) LASER driver voltage:** is the voltage driving the current source of the VCSEL.

$$\mathrm{V(Volt)} = \frac{3 \times \mathrm{DEC(LLLL)}}{4095}$$

  The voltage range is from 0 to 3 V (0x0000 to 0x0FFF).

- **(MMMM) LASER voltage:** is the voltage across the VCSEL to monitor the good health of the component.

$$V(\text{Volt}) = \frac{3 \times \text{DEC}(\text{MMMM})}{4095}$$

The voltage range is from 0 to 3 V (0x0000 to 0x0FFF).

- **(NNNN) EP temperature:** is the temperature of the main electronic board.

$$R_{NTC}(\text{Ohm}) = \frac{47\,000 \times X}{1 - X} \quad \text{with} \quad X = \frac{\text{DEC}(\text{NNNN})}{4095}$$

$$T(°C) = \frac{4100 \times 298.15}{298.15 \times \ln(10^{-5} \times R_{NTC}) + 4100} - 273.14$$

- **(OOOO) mRO-50 status:**

bit 00: CPULowPower mode 0 = DISABLE | 1 = ENABLE
bit 01: state lock LASER current / temperature LASER 0 = CLOSE | 1 = OPEN
bit 02: not used*
bit 03: state of the thermal compensation 0 = ON | 1 = OFF
bit 04: state of the crystal oscillator control loop 0 = CLOSE | 1 = OPEN
bit 05: not used*
bit 06: Forget MON_satom PIL_vc loop_0 0 = NO | 1 = YES (internal logic)
bit 07: Forget MON_satom PIL_vc loop_1 0 = NO | 1 = YES (internal logic)
bit 08: modulation status 0 = OFF | 1 = ON (internal logic)
bit 09: Need sync 0 = NO | 1 = YES (internal logic)
bit 10: temperature of the glass cell ready ? 0 = NO | 1 = YES
bit 11: temperature of the LASER ready ? 0 = NO | 1 = YES
bit 12: Need update R1 and R5 0 = NO | 1 = YES (internal logic)
bit 13: not used*
bit 14: clock locked ? 0 = NO | 1 = YES
bit 15: auto-start 0 = DISABLE | 1= ENABLE

*always in state 0.

IMPORTANT NOTE

Commands may not be taken into account or the mRO-50 may return incorrect information during about 200 ms every 3 days due to an internal update of parameters.

4.8.4 Center frequency adjustment

The output frequency is adjustable digitally and by applying an analog voltage to pin #1.

Analog voltage: must be low noise and stable to avoid any degradation of the mRO-50 performance. This voltage is added to the voltage driving the current source of the coils. Safran Trusted 4D recommends a buffer as close as possible to pin #1.

IMPORTANT NOTE

Pin #1 (IN analog frequency adjustment) must not be connected to any voltage potential if not grounded.

Care must be taken to the stability of the voltage applied to pin #1 to not degrade the long term frequency stability of the clock.

Digital frequency adjustment: is divided into fine and coarse. The fine tuning acts on the polarization of the C field and the coarse on the frequency of the digital PLL. The value is coded on 16 bits but are truncated in the software.

- Fine frequency adjustment: is achieved with the command 'MON_tpcb PIL_cfield'. The C-field polarization is defined by C.
  - MON_tpcb PIL_cfield C<CR>: return the current value of C in 16 bits not signed hexadecimal in the range of 0x0640 to 0x0C80 (example: 0x0960<CRLF>).
  - MON_tpcb PIL_cfield C XX<CR>: add an offset to the current value of C. The parameter is used as long as the clock is running, a reboot will load the initial value of C. XX is a 8 bits signed hexadecimal word settable from 0x80 to 0x7F.
  - MON_tpcb PIL_cfield C XXXX<CR>: change the value of C. The parameter is used as long as the clock is running, a reboot will load the initial value of C. XXXX is a 16 bits not signed hexadecimal word settable from 0x0640 to 0x0C80.
  - MON_tpcb PIL_cfield C LOAD<CR>: return the initial value of C on 16 bits not signed hexadecimal.
  - MON_tpcb PIL_cfield C SAVE<CR>: save the current value of C as initial value.
  - MON_tpcb PIL_cfield C SAVE XXXX<CR>: save the 16 bits not signed hexadecimal word XXXX as initial value of C.
- Coarse frequency adjustment: is achieved with the command 'FD' followed by a carriage return character. The customer must change the frequency step by step waiting at least 6 seconds between each step.
  - FD<CR>: return the current value in 32 bits not signed hexadecimal in the range of 0x000000000 à 0x003FFFFF of the denominator of the fractional digital PLL.
  - FD XX<CR>: add an offset to the current value of FD. The parameter is used as long as the clock is running, a reboot will load the initial value of FD. XX is a 8 bits signed hexadecimal word settable from 0x80 to 0x7F.
  - FD XXXXXXXXX<CR>: change the value of FD. The parameter is used as long as the clock is running, a reboot will load the initial value of FD. XXXXXXXX is a 32 bits not signed hexadecimal word settable from 0x000000000 to 0x003FFFFF.
  - PLL SAVE<CR>: save the current value of FD as initial FD.

IMPORTANT NOTE

Safran Trusted 4D recommends the fine frequency tuning function. A wrong use of the coarse tuning may unlock the clock.

4.8.5 ID

The 'ID' command returns information about the clock in ASCII as below.
VVVVVVVVVVVVVVVVVVVVVVVVV WWWWWWWW XXXXXXXXXXXXX YYYYYYYY ZZZZZZZZ ZZZZZZZZ ZZZZZZZZ<cr><lf>

- (VVVVVVVVVVVVVVVVVVVVVVVVV) Part number
- (WWWWWWWW) Serial number
- (XXXXXXXXXXXXX) firmware version
- (YYYYYYYY) developer information
- (ZZZZZZZZ ZZZZZZZZ ZZZZZZZZ) checksum

4.9 Lock monitor

LED device may be directly connected to the '\lock monitor output' according to Figure 8.

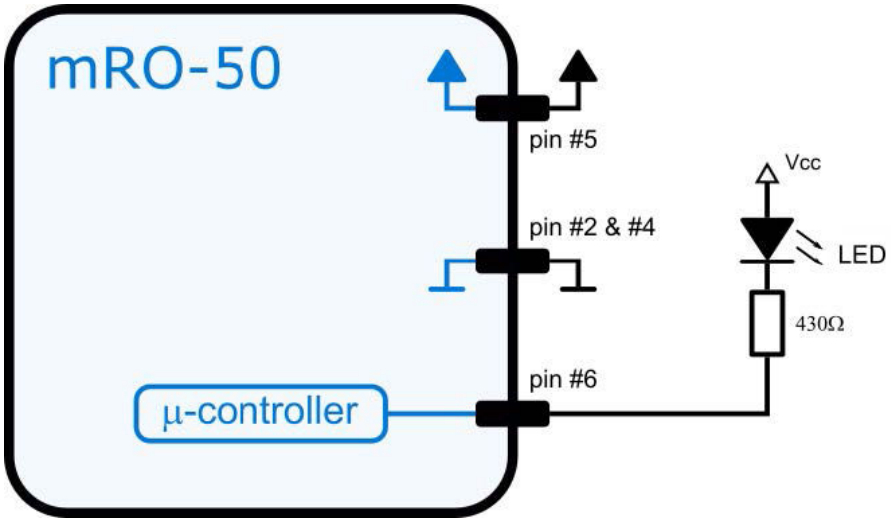

Figure 8: electronic scheme for LED \lock monitoring

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