Fiber-optic time and frequency distribution system OSTT-2
user manual for standard option devices S/N X.X provided for XX

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I. Introduction

The OSTT-2 distribution system is capable of delivering the reference time and frequency signals to a remote location. Its unique feature is an active compensation of a propagation delay fluctuations, observed in optical fibers due to temperature variations, mechanical stresses and vibrations. Using bidirectional signal transmission in one optical fiber, after measuring a round-trip delay and applying some corrections, the input-output delay may be calibrated without help of any additional time transfer systems.

Besides metrological applications, like clock comparisons, the system may be used for delivering the ultimate quality time and frequency signals to the users not maintaining their own clocks and/or timescales.

The system consist of a local (transmitting) module installed in a laboratory delivering time and frequency signals, and a remote (receiving) module, installed in some distant location - see Fig. 1. The modules should be connected by a singlemode optical fiber.

Fig. 1. Local and remote modules.

II. Specifications of a basic setup

- Frequency signal: 10MHz (5 MHz, 100MHz options available).
- Time signal: 1PPS, 100PPS, 1000PPS (phase synchronous with the frequency signal).
- Optical fiber: one singlemode fiber of any type (e.g. G.652, G.655), APC connectors.
- Maximum optical attenuation: 25 dB (equivalent to 50 - 100 km of fiber, depending on the link quality). Minimum optical attenuation: 6 dB.
- Delay correction range: 100 ns (enough for 100 km of fiber in typical environmental conditions).
- Frequency transfer stability: ADEV < 1×10^{-12} for 1 s averaging, < 3×10^{-17} for 10^5 s averaging.
- Time transfer stability: TDEV < 3 ps for 10 s averaging, < 1 ps for 10^5 s averaging.
- Time calibration uncertainty: 15 ps (assuming 5 ps uncertainty of time interval measurements and 5 ps/nm uncertainty of fiber dispersion measurement[1].

[1] See also Metrologia 50 (2013) p. 137.

III. Principle of operation

The input frequency signal (10 MHz in standard option) and time signal (1PPS to 1kPPS) are combined in the coder (see block diagram in Fig. 2). The integrated signal passes the variable delay block, then is converted to the optical domain, and feeds the fiber through the optical circulator. In the remote module the signal is retransmitted back to the local module. After passing the second variable delay block and the decoder, it is then phase-compared with the forward-direction signal. The phase detector senses and eliminates any phase fluctuations of the feedback signal by simultaneous steering of the two delay lines. This way the changes of the fiber propagation delay are compensated by automatic tuning of the delay lines.

To avoid ambiguous locking of the system, the periods of the signals entering the phase detector should be higher than the tuning range of the delay lines (1 µs and 100 ns respectively). Thus to obtain the unique, repeatable locking condition a stepper (digital delay) capable of shifting the signal in 20 ns-steps is introduced at one of the inputs of phase detector. The stepper delay should be set after connecting the local and remote module via a target fiber, and will not need any further adjustment as long as the fiber delay fluctuations do not exceed the tuning range of the variable delay lines.

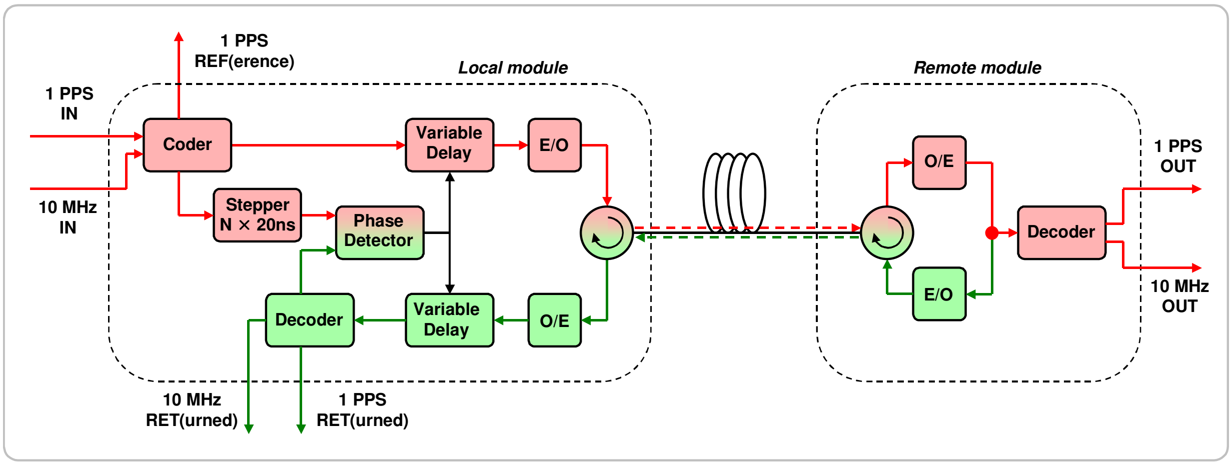
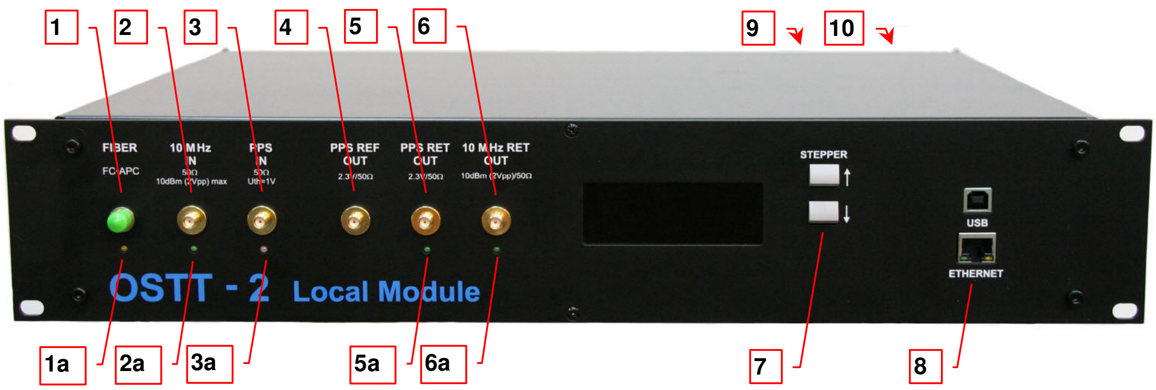
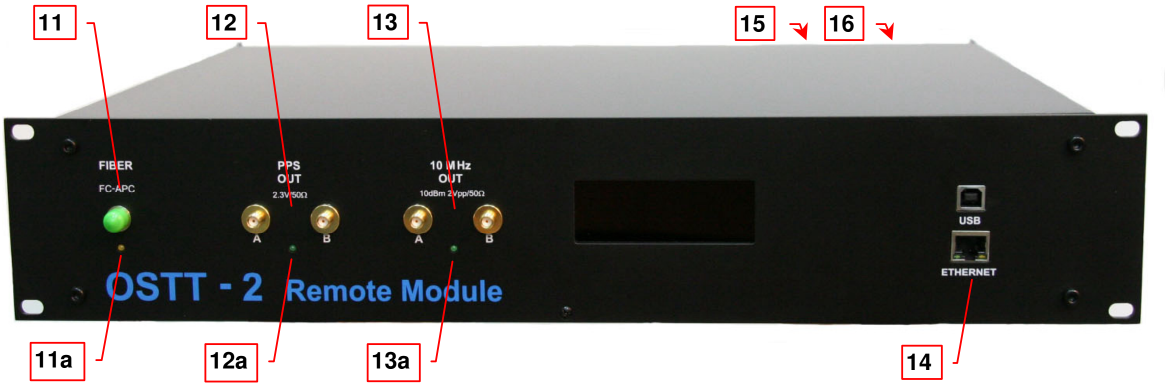


Fig. 2. Block diagram of the system.

IV. Interfaces description



(a)



(b)

Fig. 3. Connectors location in local module (a) and remote module (b).

Local module

1. Optical input/output connector; FC-APC type, output wavelength 1549.32 nm, output power -2 dBm.

1a. LED indicating laser transmitter status; continuous yellow light means proper operation, blinking means unstable laser operation, possibly caused by lack of system synchronization, or laser overheating.

2. 10 MHz input; SMA connector, 50 Ω DC termination, 0 dBm to 10 dBm input signal level, sinus or square wave.

2a. LED indicating synchronization of inner oscillators to the input frequency signal; continuous green light means synchronization, no light or blinking means no synchronization, i.e. system malfunction .

3. PPS input; SMA connector, 50 Ω DC termination, 1 PPS to 1000 PPS, rising edge is treated as the time marking event; **PPS signal should be coherent with 10 MHz signal.**

3a. LED indicating PPS signal detection; green light indicates presence of input signal, red light marks a risk of ambiguous coding of PPS signal (see sec. V).

4. PPS REF(erence) output; SMA connector, 2.25V at 50 Ω termination, used for calibration.

5. PPS RET(turned) output; SMA connector, 2.25V at 50 Ω termination, used for calibration.

5a. LED indicating returned PPS signal detection.

6. 10 MHz RET(turned) auxiliary output; SMA connector, 10 dBm at 50 Ω termination, may be used for round-trip frequency stability evaluation.

6a. LED indicating detection of the returned frequency signal; continuous green light means detection of returned 10 MHz signal, no light or blinking means no detection, i.e. system malfunction.

7. STEPPER up and down push buttons; each press increments/decrements the delay of the stepper by 20 ns; the state of the stepper is shown at the LCD display; after reaching the last state - ‘49’ - the next press shifts the stepper to the initial state - ‘0’.

8. Remote control and monitoring; allows to change the Stepper state and to read the status information.

9. Fuse socket (at the rear panel); T 2 A fuse.

10. DC power supply (at the rear panel); 12 V nominal, 10 V to 18 V acceptable, maximum supply current: 2A.

Remote module

11. Optical input/output connector; FC-APC type, output wavelength 1548.51 nm, output power -2 dBm.
11a. LED indicating laser transmitter status; continuous yellow light means proper operation, blinking means unstable laser operation, possibly caused by lack of system synchronization, or laser overheating.
12. Doubled PPS output; SMA connector, 2.25V at 50 Ω termination, rising edge of output pulse is treated as the time marking event, pulse duration is 20 µs, regardless of the input PPS duration. Skew between A and B outputs is not greater than 5 ps.
12a. LED indicating PPS signal detection.
13. Doubled 10 MHz output; SMA connector, 10 dBm at 50 Ω termination.
13a. LED indicating detection of the frequency signal; continuous green light means detection of 10 MHz signal, no light or blinking means no detection, i.e. system malfunction.
14. Remote monitoring; allows to read the status information.
15. Fuse socket (at the rear panel); T 2 A fuse.
16. DC power supply (at the rear panel); 12 V nominal, 10 V to 18 V acceptable, maximum supply current: 2A.

Displays

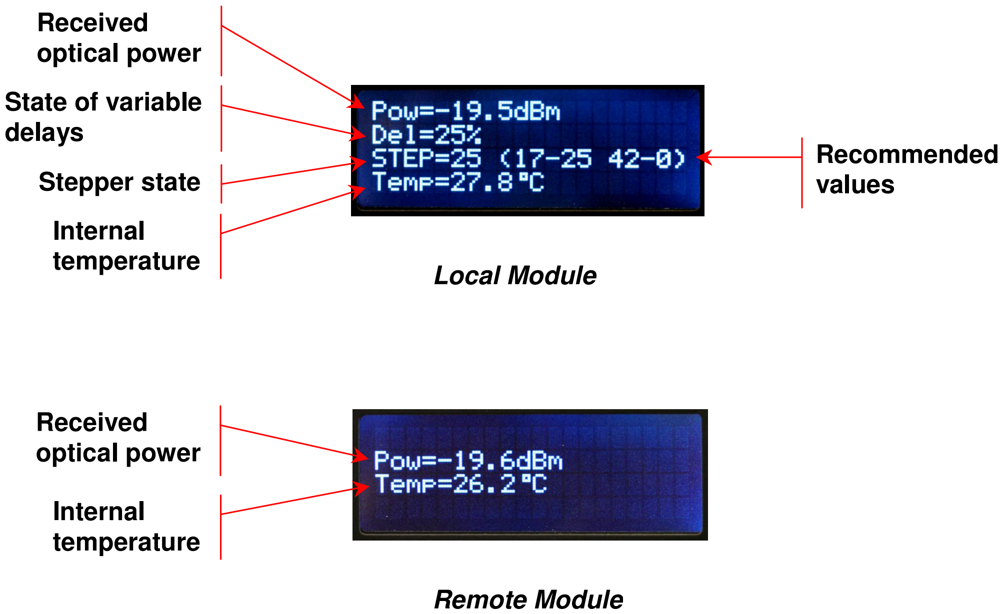


Fig. 4. LCD panels.

V. Installation

Generally optical and electrical signals at the local and remote sides may be connected/disconnected in any arbitral sequence. It is however recommended to disconnect both 10 MHz and PPS input signals before powering-off the local module.

The laser wavelength stabilization system presents some vulnerability on ambient temperature, so it is important, that module's cases are able to dissipate the head in an undisturbed manner, and that they are not exposed to serious heating by neighboring equipment. The best performance will be obtained in air-conditioned environment with good temperature stabilization.

To obtain good transfer stability and calibration accuracy, high quality electrical cables should be used. The SMA connectors should be screw with spanner. Loose connectors without screw fixture, as BNC, may cause significant performance degradation.

Recommended installation sequence:

1. **Connect the optical fiber**. Be sure the connectors are clean! Use only cleaning materials designated for optics. When connecting FC-APC connectors be sure than the positioning key is inserted properly into the gap in the socket. When connecting the modules with a patchcord or short fiber with attenuation below 6 dB, use additional attenuator. Optical fiber may be reconnected during operation of the system, but direct eye exposure to a laser beam should be avoided.

2. **Connect the power supply** to the connectors located at the rear panels. The LCD displays should start up, and LEDs 1a and 11a should blink. In order to obtain a thermal equilibrium, it is recommended to leave the devices powered-on for at least half an hour before the next step.

3. **Connect the 10 MHz input signal** to the local module. At this point, when both modules are powered-on and optical fiber is properly connected, LEDs 1a, 2a, 6a in the local module and 11a, 13a in the remote module should glow continuously. The system is then ready for setting the operating point of the delay lines (next step).

4. **Set the proper operating point of the variable delay lines**, using stepper push-buttons.
   To obtain the proper operating point increment (or decrement) the state of the stepper (which is displayed at the LCD panel) by pressing the buttons. Repeat pressing the button until the operating point of the variable delays is closed to the middle of its tuning range, which corresponds to Del value close to 50% at the LCD panel of the local module

   When initially the Del value is 0% or 100%, it is normal that some number of changes of the stepper state do not affects the Del. In this case continue incrementing (or decrementing) the stepper. After some number of steps Del will start to change gradually, about 10% for one step.

   After setting the operating point of the delay lines the system reaches its functionality – the propagation delay is then stabilized, thus the 10 MHz signal at the output of the remote module should reach desired stability, and the time transfer calibration may be performed.
   However, the best performance, especially in the sense of the long term stability, may be obtained when the stepper state is in the range <17, 25>, or <42, 0>. If after setting the operating point the stepper state is outside this ranges, one may change it by adding an extra patchcord in series with the target fiber. Each 2 m of the patchcord corresponds with

the need of incrementing the steeper state by one. The attached set of patchcords (3 m, 2×10 m and 35 m) allows setting the stepper in one of its recommended states in any case.

5. **Connect the 1 PPS input signal** to the local module. (Connecting 1 PPS signal is not obligatory when the system is used only for frequency distribution.) LED 3a should emit in green. Red light mark a risk of ambiguous coding of 1 PPS signal, because of a hazardous phase relationship between signals processed in the coder. Although the risk of ambiguous coding is very small, it is recommended to change the phase relation between the 10 MHZ and 1 PPS signals by changing the length of the cable providing 1 PPS signal by a meter or so. When the local and remote modules are properly connected by the fiber, also LEDs 5a and 12a should glow. During connecting the PPS input signal a single phase hop of the 10 MHz signal at the remote output may be observed, because of possible re-synchronization process.

6. **Optionally connect the remote control** via USB or Ethernet port. To avoid possible perturbations during device booting period, the USB cable should be plugged-in **not earlier** than 1 minute after powering-up the device.

VI. Calibration of time transfer

The calibration of time transfer is based on two time interval measurements, the fiber chromatic dispersion measurement (or estimation), and the Sagnac effect calculation.

The active stabilization of the delay makes the delay between the 1 PPS REF(erence) and 1 PPS RET(urned) points constant (see Fig. 5). Measuring the delay from 1 PPS REF to 1 PPS RET ($\tau_{REF \to RET}$), the delay from 1 PPS REF to the 1 PPS OUT in the remote module ($\tau_{REF \to OUT}$) may be estimated to the first order as a half of this round-trip delay. After applying necessary corrections it may be expressed finally as:

$$\tau_{REF \to OUT} = \frac{1}{2}\left[\tau_{REF \to RET} + \left(\tau_{FIB\_F} - \tau_{FIB\_B}\right) + \tau_C\right],$$

where $\tau_{FIB\_F} - \tau_{FIB\_B}$ is the difference of the fiber propagation delay in forward and backward directions, caused by the chromatic dispersion and the Sagnac effect, and τ_C is (nominally) constant hardware term.

To calibrate the total delay from the UTC(k) reference point to the remote output, the delay from UTC to 1 PPS REF ($\tau_{UTC(k) \to REF}$) should be measured and added to the previous formula:

$$\tau_{UTC(k) \to OUT} = \tau_{UTC(k) \to REF} + \frac{1}{2}\left[\tau_{REF \to RET} + \left(\tau_{FIB\_F} - \tau_{FIB\_B}\right) + \tau_C\right].$$

It should be stressed that the process of PPS signal coding relay on 10 MHz IN signal, so the delay from PPS IN to PPS REF, and thus also the delay from UTC(k) to PPS REF is constant as long as the phase relation between signals connected to 10 MHz IN and PPS IN is constant. Thus both these signals should be provided from the same source.

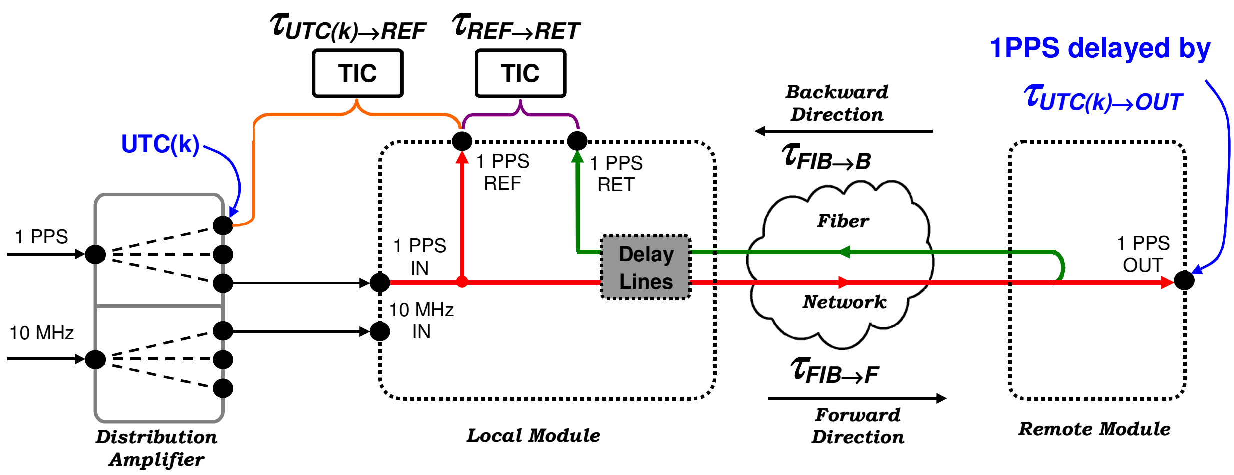


Fig. 5 Time calibration.

Basically, the term $\tau_{FIB\_F} - \tau_{FIB\_B}$ may be calculated using the formula:

$$\tau_{FIB\_F} - \tau_{FIB\_B} = D(\lambda_F - \lambda_B) \pm \frac{4\omega A_E}{c^2},$$

where λ_F and λ_B are the wavelengths of the local (forward) and remote (backward) lasers, D is the cumulated chromatic dispersion of the fiber link. The last term, i.e. $4\omega A_E / c^2$ is the

Sagnac correction, where ω is the angular speed of rotation of the Earth, A_E is the area of the projection of the surface swept out by a vector extending from the centre of the Earth to the fiber carrying the optical signal onto the equatorial plane and c is the speed of light in vacuum. The Sagnac term should be taken with (+) sign when the remote module of the system is located to the east of the local one.

In practice, the first right-hand term in above equation might need slight correction:

$$\tau_{FIB\_F} - \tau_{FIB\_B} = \Gamma D(\lambda_F - \lambda_B) \pm \frac{4\omega A_E}{c^2},$$

where Γ is a close-to-one empirical factor concern with some second-order effect - an interaction of the laser chirping with the chromatic dispersion of the fiber. Nominally, when both local and remote lasers display the same chirping characteristics, $\Gamma = 1$, but in case of some noticeable lasers mismatch slightly different value should be used.

Calibration procedure

Calibration may be performed when both local and remote modules reach temperature equilibrium, LEDs 2a, 6a and 13a glow continuously, Del is close to 50%, and all cables and connectors are steadily fixed.

1. Pre-defined values:

OSTT-2 S/N: X.X			
Γ	λ_F	λ_B	τ_C
0.9737	1549.32 nm	1548.51 nm	54.920 ns

2. The delay $\tau_{REF \to RET}$ (see Fig. 5) should be measured with a highly accurate TIC. Because the PPS REF and PPS RET outputs produce pulses of very similar characteristics, the TIC threshold level do not affect the measurement significantly. The recommended threshold is in the range of 0.5 V to 1.5 V.

3. Determining accumulated chromatic dispersion of the fiber D:
   The best solution is to measure the chromatic dispersion of the target fiber at wavelengths near to λ_F (1549.32 nm) and λ_B (1548.51 nm) with a high accuracy chromatic dispersion analyzer, and take the mean value as D used in calculations. When the available data are for different wavelengths, linear (or cubic) interpolation may be used to determine the dispersion at the central wavelength defined as $(\lambda_F + \lambda_B)/2$.
   The second option is to estimate the chromatic dispersion basing on the knowledge of the fiber length and type. For G.652 fiber (other names: standard single-mode fiber, SMF-28) the dispersion coefficient is about 17 ps/nm/km, for G.655 (other names: NZDSF, LEAF) it is usually around 6.5 ps/nm/km. Thus accumulated dispersion may be estimated by multiplying these values by the length of the fiber. It should be stressed however that uncertainty of such estimation is up to 10 - 15%.

4. The Sagnac correction needs the estimation of the area of the projection onto the equatorial plane of the surface swept out by a vector extending from the center of the Earth to the fiber carrying the optical signal (A_E). For link distances in range of hundred kilometers the correction is below 1 ns, thus the simple estimation based on the local and remote modules

coordinates is sufficient. Using this approach $A_E \approx 0.5RL\cos\alpha$, where R is mean Earth radius, L is the west-east distance of local and remote modules and α is the latitude of the region of installation.

5. To obtain the total delay from UTC(k) point to the remote PPS output, the time interval from UTC(k) to PPS REF should be also measured and added to $\tau_{REF\rightarrow OUT}$. Because the PPS pulses generated at UTC(k) reference output and PPS REF output may differ in amplitude and shape, the measured value may depends on the TIC threshold level, which should be taken into consideration.

Example of calibration

Let us consider the following data:

- fiber dispersion was measured at 1548 nm and 1550 nm, the results are 814.64 ps/nm and 826.66 ps/nm, respectively,
- the fiber length is 105 km (data not needed for calculations),
- the remote module is located 52 km west and 30 km south from the local one, both are near 41° latitude,
- $\tau_{REF\rightarrow RET}$ was measured as 511362.232 ns.

Calculations:

- after linear interpolation the chromatic dispersion D at central wavelength (1548.915 nm) is 820.14 ps/nm,
- the term $\Gamma D(\lambda_F - \lambda_B)$ is thus 647 ps,
- the area A_E may be estimated as $A_E \approx 0.5RL\cos\alpha$, where R is mean Earth radius (6370 km), L is the west-east distance of local and remote modules (52 km), and α is latitude (41°);
- the term $4\omega A_E / c^2$ is thus 404 ps and should be taken with (-) sign because the remote module is located to the west from the local one,
- $\tau_{FIB\_F} - \tau_{FIB\_B}$ may be calculated as 647 ps - 404 ps = 243 ps,
- finally $\tau_{REF\rightarrow OUT}$ is: 0.5× (511362232 ps + 243 ps + 54920 ps) = 255708698 ps.

VII. USB and remote communication with OSTT2 console

There are two possibilities of accessing OSTT2 programming console: via USB or Ethernet port. The simple Command Line Interface (CLI) allows to read the device status and set the stepper delay and network interface configuration. There is also a possibility of shifting the wavelength of the local module laser, which is useful when performing the autonomous measurement of the chromatic dispersion (see Appendix I).

Warning: To avoid possible perturbations during device booting period, the USB cable should be plugged-in not earlier than 1 minute after powering-up the device.

USB connection

Before controlling the OSTT2 devices via USB connection, a virtual COM driver should be installed on the PC, which allows you to use the USB connection as a virtual COM port. The driver files are included to the CD provided with the devices, and also may be downloaded directly from the interface manufacture's web page:
http://www.ftdichip.com/Drivers/VCP.htm

After installing the driver, the connection between PC and OSTT2 system via USB could be established. A new COM port should appear in the OS resources. (In Windows it will appear in: Control Panel -> System -> Device Manager (see Fig. 6)

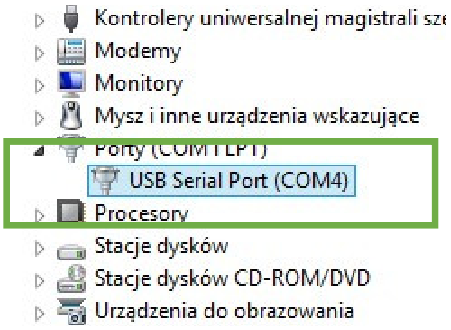
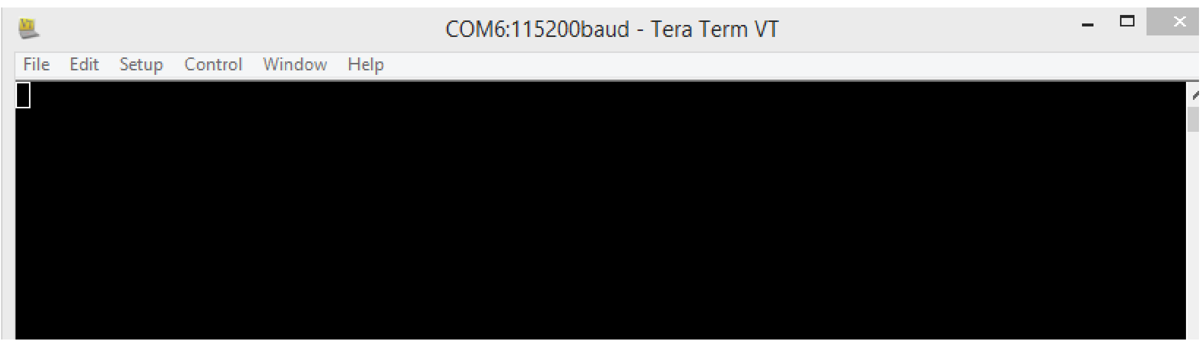


Fig. 6. FTDI virtual serial listed as port COM4 in Devices Manager.

Then, using any kind of Terminal application available in the particular OS (e.g. in Windows OS: putty[2], Tera Term[3], in Linux: putty, minicom[4]), appropriate commands (pressed on a keyboard) may be send to the Local/Remote devices. After starting the Terminal the virtual COM should be configured as follows:

Bits per Second: 115200, Data Bits: 8, Parity: None, Stop Bits: 1, Flow Control: none.

In this point the connection should be operational. Initially the terminal window may be empty:



[2]http://www.putty.org
[3]http://logmett.com
[4]https://help.ubuntu.com/community/Minicom

but after pressing <ENTER> key the login prompt should appear:

```
COM5:115200baud - Tera Term VT
File  Edit  Setup  Control  Window  Help

OSTT2 Remote Module - ubuntu 12.04.3 LTS OSTT2-Remote tty00
OSTT2-Remote login:
```

Please use:

login: ***user***
password: ***xx***

After that, the OSTT2 system menu will appear (Fig. 7); one can always get *help* by typing:
help <Enter> or *Ctrl + i*
If no any user action in the console windows is detect during more than 10 minutes, the system will logout the user automatically.

a)

```
***********************************************************
* Optical System for Time Transfer,  AGH DoE OPTO LAB *
* OSTT2 Transfer System Local Device rel:4.4
***********************************************************
--- help or Ctrl+I   system help
--- status       - system status
--- stepper inc - increment stepper delay
--- stepper dec - decrement stepper delay
--- lambda inc  - increment laser length
--- lambda dec  - decrement laser length
--- lambda nom  - set nominal laser value
--- net       - network information
--- net set   - new network settings
--- reboot    - system rebooting
--- Ctrl+]    - logout

OSTT2 Local>
```

b)

```
***********************************************************
* Optical System for Time Transfer,  AGH DoE OPTO LAB *
* OSTT2 Remote Device rel:4.4
***********************************************************
--- help or Ctrl+I   system help
--- status       - OSTT2 system status
--- net       - network information
--- net set   - new network settings
--- reboot    - system rebooting
--- Ctrl+]    - logout

OSTT2 Remote >
```

Fig. 7. User menu in OSTT2 Local (a) and Remote (b) device.

Commands

status – this command lists all OSTT2 Local/Remote internal parameters - see Fig. 8.

a)

```
OSTT2 Local>status
10MHz input signal detected:  NO!
PPS input signal detected:    --
PPS phase correct:            --
Feedback signal  detected:    --
Received optical power:       NO!
Delay compensation:           --
Inner case temperature:       OK        21.0°C

Laser wavelength locked:      YES
Laser temperature control:    OK        TEC usage: 2%
```

b)

```
OSTT2 Remote >status

Remote module synchronized:  NO!
PPS signal detected:         --
Received optical power:      NO!
Inner case temperature:      OK        23.9°C

Laser wavelength locked:     YES
Laser temperature control:   OK        TEC usage: 2%


OSTT2 Remote >
```

Fig. 8. Response on *status* command in OSTT2 Local(a) and Remote (b) device

stepper inc - increment stepper delay

```
OSTT2 Local>stepper inc
DEL=6
```

stepper dec - decrement stepper delay

```
OSTT2 Local>stepper dec
DEL=5
```

net – this command checks Ethernet IP status and settings:

```
OSTT2 Remote >net
Network:
--- configuration: dhcp
--- ip:   10.10.200.104
--- mac:  c8:a0:30:ac:8c:00
--- mask: 255.255.255.0
--- gate: 10.10.200.1
```

net set – this command allows to set Ethernet interface parameters. First the static or dynamic host IP configuration should by selected. If one choose static, the following parameters should be entered: host IP, network mask and gateway address.

```
OSTT2 Remote >net set
Network configuration: static / dynamic (s/d):s
Static network configuration
ip: 10.10.200.5
mask:255.255.255.0
gateway:10.10.200.1
Please confirm data (y/n):y
```

The system should be rebooted to update network configuration.

reboot - this command reboots the system
Ctrl+] - this command closes the terminal session and logout user; there is also automatic logout after 10 minutes of user no activity.

Remote access via SSH connection

The OSTT2 system allows remote login to the system console (Command Line Interface), using SSH session. Before starting the session one must configure terminal program (e.g. putty, TeraTerm) by entering the OSTT2 Local (Remote) Device's IP address (Fig. 9). If the OSTT2 device is connected via USB, the ***net*** command shows IP assigned to Ethernet interface by DHCP server, or defined earlier (static IP). Use this address to connect OSTT2 device over Internet.
Do not use simultaneously both USB and Ethernet connection to the system.

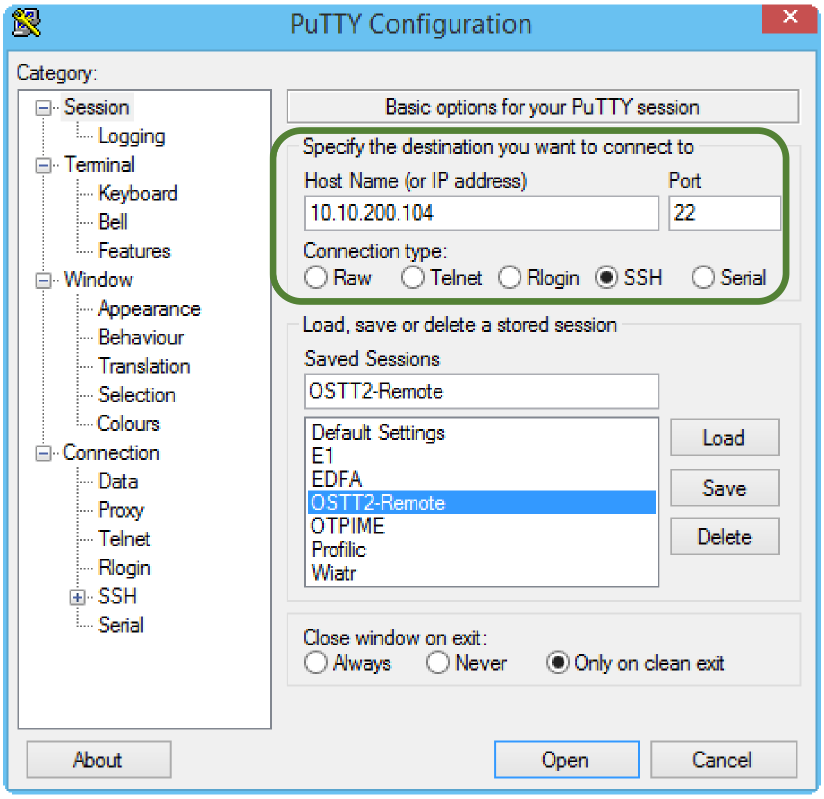


Fig. 9. PuTTY terminal - configuration window.

When the OSTT2 Local\Remote modules are connected to a local network and UPnP devices discovering is enabled in your computer, you can find these devices in *My Network Places* as *Another Devices*:

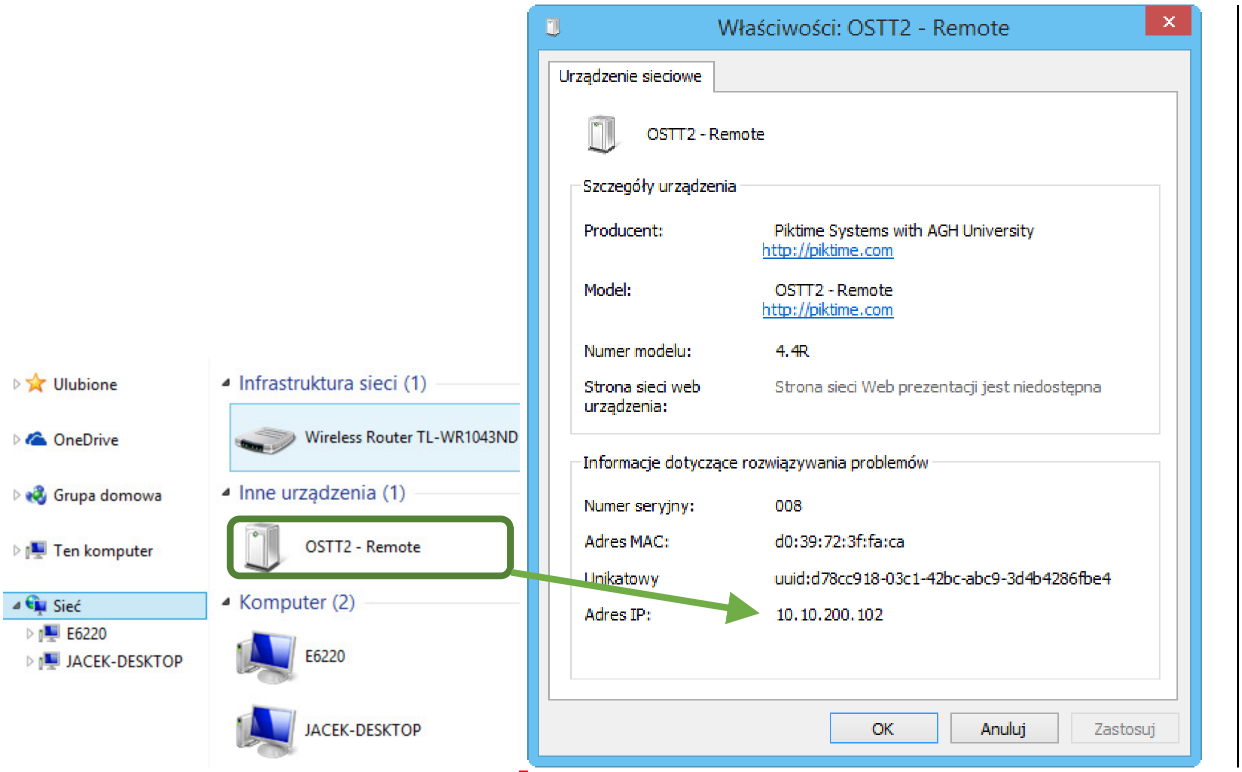


Fig. 10. OSTT-2 devices detected as UPnP devices.

During SSH client-server negotiation one should confirm the server side (OSTT2) RSA2 key fingerprint:

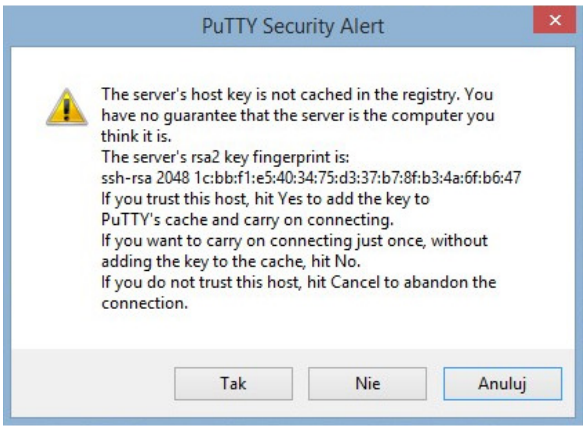


Fig. 11. OSTT2 SSH connection hey.

The terminal view after successful login is shown in Fig 12.

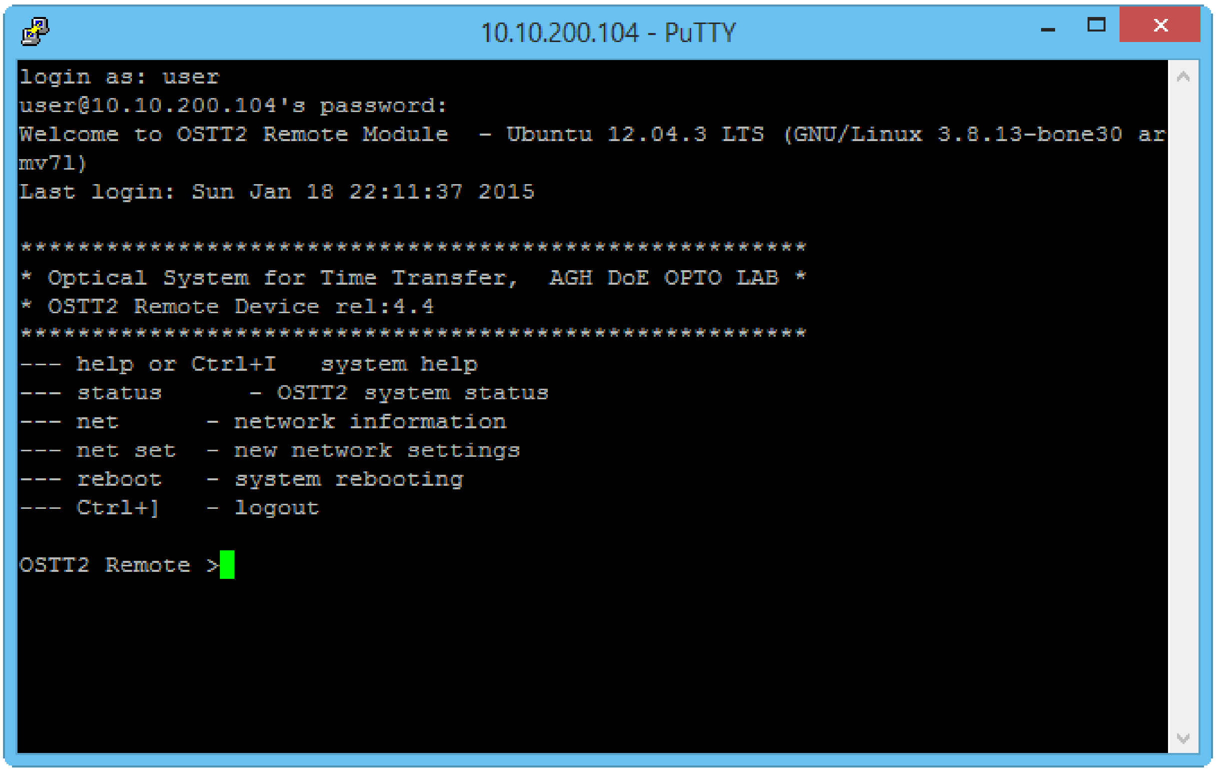


Fig. 12. OSTT2 menu accessed via SSH Ethernet connection