

# **Spectral Phase Interferometry For Direct Electric Field Reconstruction**

**SPIDER**

**MODEL Avoca-120**

**Instruction Manual**

**Del Mar Photonics**

4119 Twilight Ridge

San Diego, CA 92130 USA

Tel::858.876.3133

Fax::858.630.2376

E-mail::sales@dmphotonics.com

Web::www.dmphotonics.com

## **General Safety Information**

In order to ensure the safe operation and optimal performance of the product, please follow these warnings in addition to the other information contained elsewhere in this document.

**WARNING:** If this instrument is used in a manner not specified in this document, the protection provided by the instrument may be impaired.

**TABLE OF CONTENTS**

	PAGE
LIST OF TABLES.....	iv
LIST OF FIGURES .....	v
CHAPTER	
1 Manifest .....	1
2 Specifications.....	2
3 Principle Of Operation .....	3
4 Apparatus Description .....	7
5 Unpacking Avoca-120 .....	10
6 Device Installation And Setup.....	12
6.1 Requirements .....	12
6.2 Efrat Software Installation .....	12
6.3 Hardware Installation .....	13
6.4 Driver Configuration .....	13
6.5 Loading Spectral Calibration .....	13
6.6 Loading Spectral Sensitivity Database .....	13
6.7 End Note.....	14
7 Measuring Procedure .....	15
REFERENCES .....	18

**LIST OF TABLES**

	PAGE
Table 1.1 Consolidated shipping manifest. ....	1
Table 2.1 Operating specifications for Avoca-120. ....	2

## LIST OF FIGURES

	PAGE
Figure 3.1 Operational schematic for SPIDER.....	3
Figure 3.2 Experimental spectral interferogram (SPIDERgram) used to reconstruct the spectral phase. ....	4
Figure 3.3 Schematical diagram of the procedure for extracting the spectral phase from an interferogram. ....	5
Figure 3.4 Fourier transform of the SPIDERgram. ....	6
Figure 4.1 Optical schematic for Avoca-120. ....	9
Figure 5.1 System schematic for Avoca-120. ....	11
Figure 7.1 Delay line micrometer calibration position for center wavelength. ....	16

# CHAPTER 1

## Manifest

**Table 1.1. Consolidated shipping manifest.**

Part	Quantity	Note
Box	1	Opto-mechanical box
Table Clamps	4	Clamps for securing the Optical Unit on optical table
Efrat Software	1	Software for controlling Avoca-120 SPIDER unit
Manual	1	This document

## CHAPTER 2

### Specifications

**Table 2.1. Operating specifications for Avoca-120.**

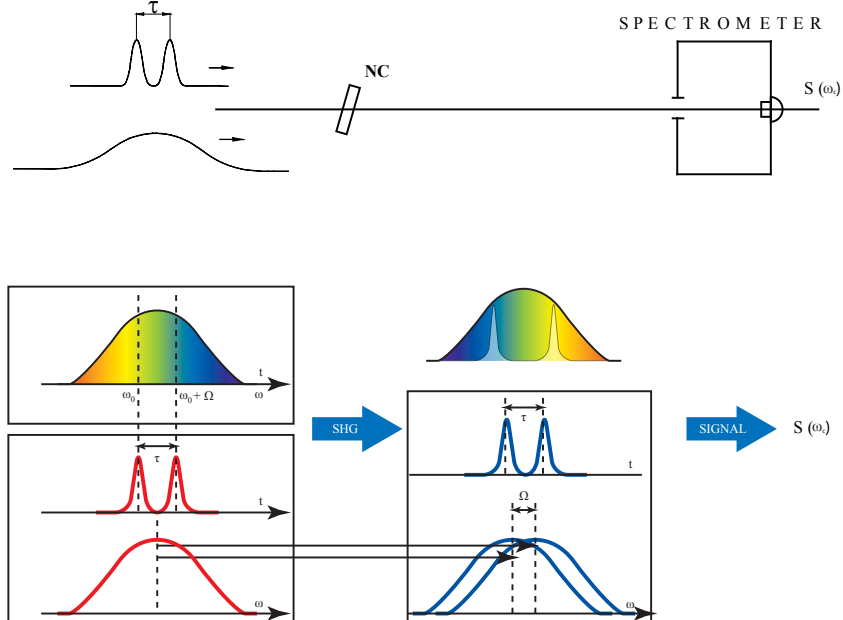
Wavelength range	740-860 nm
Pulse duration	30-120 fs
Minimum required input power	100 mW average for 100 MHz repetition rate 1 mW for 1kHz repetition rate
Input polarization	linear-horizontal
Input beam diameter	<4 mm
Input beam height	110-140 mm
Dimensions	700 mm x 350 mm x 180 mm

## CHAPTER 3

### Principle Of Operation

The basic principle of operation for Avoca-120 is a version of spectral shearing interferometry[1][2] (SSI). This version is known as SPIDER - Spectral Phase Interferometry for Direct Electric field Reconstruction[3][4]. In SSI two ultrashort pulses are shifted in frequency with respect to each other and then are recombined to produce an interference pattern in a spectrometer. A very simple noniterative algorithm of recorded spectral interferograms gives the spectral phase of the ultrashort light pulse to be characterized. In addition to independently measuring the pulse spectrum, after a Fourier transform the time-dependent phase and intensity is obtained.

The operational schematic of the Avoca-120 SPIDER device is shown in Figure 3.1. Two identical pulses are delayed with respect to one another in time and frequency mixed with a stretched pulse in a nonlinear crystal. Each pulse replica is up-converted with a different frequency slice, and consequently, are spectrally sheared from each other. Note, the central frequency of the up-converted pulses is near  $2\omega_0$ , where  $\omega_0$  is the central frequency of the measured pulse.



**Figure 3.1. Operational schematic for SPIDER.**

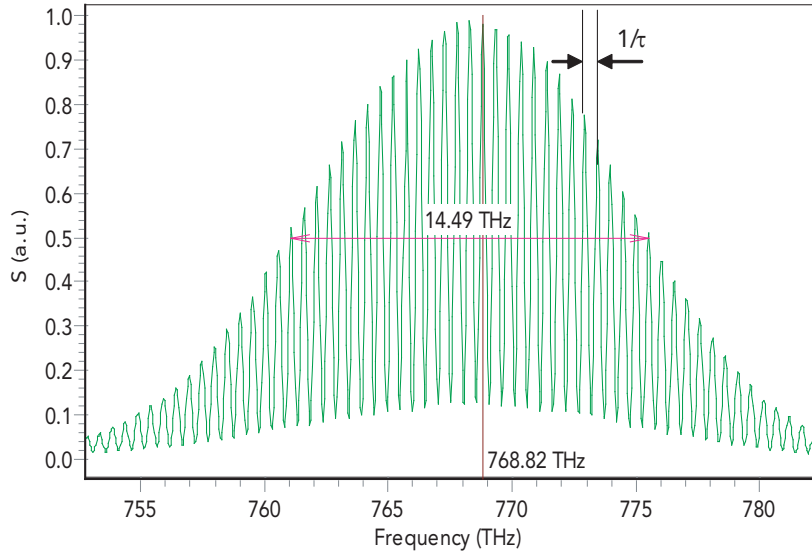


The output signal  $S(\omega_c)$  from the spectrometer is related to the input pulse spectrum by

$$S(\omega_c) = \left| \tilde{E}(\omega_c) \right|^2 + \left| \tilde{E}(\omega_c + \Omega) \right|^2 + 2 \left| \tilde{E}(\omega_c) \right| \left| \tilde{E}(\omega_c + \Omega) \right| \cos [\Phi_\omega(\omega_c + \Omega) - \Phi_\omega(\omega_c) + \omega_c \tau], \quad (3.1)$$

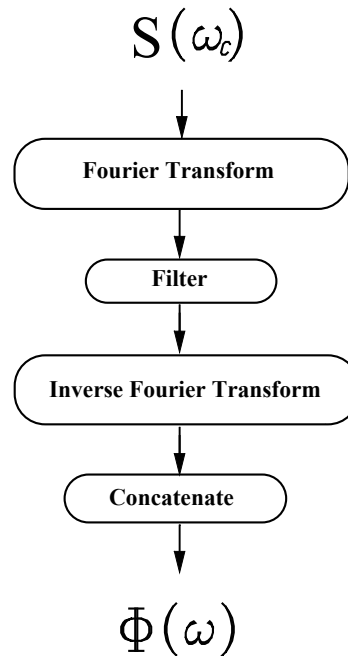
where  $\tilde{E}(\omega)$  is the complex representation of the input pulse electric field,  $\Omega$  is the frequency shear,  $\tau$  is the time delay between the two replica pulses, and  $\omega_c$  is the variable center passband frequency of the spectrometer. The first two terms on the right side of Equation 3.1 are the individual spectra of the test pulse and its frequency sheared replica, respectively. The third term provides the spectral phase in the form of the phase difference between spectral components separated by the shear  $\Omega$ . One obtains the spectral phase for a set of discrete frequencies separated by  $\Omega$  from the spectral phase differences by simply adding up the appropriate phase differences. The spectral amplitude at these frequencies is obtained from the square root of an independently recorded reference pulse spectrum.

An example of the experimental spectral interferogram from a pair of spectrally shifted pulses is shown in Figure 3.2. The nominal fringe spacing is  $1/\tau$  (in linear frequency units). Spectral phase of the measured pulse manifests itself as deviations from the nominal fringe spacing.



**Figure 3.2. Experimental spectral interferogram (SPIDERgram) used to reconstruct the spectral phase.**

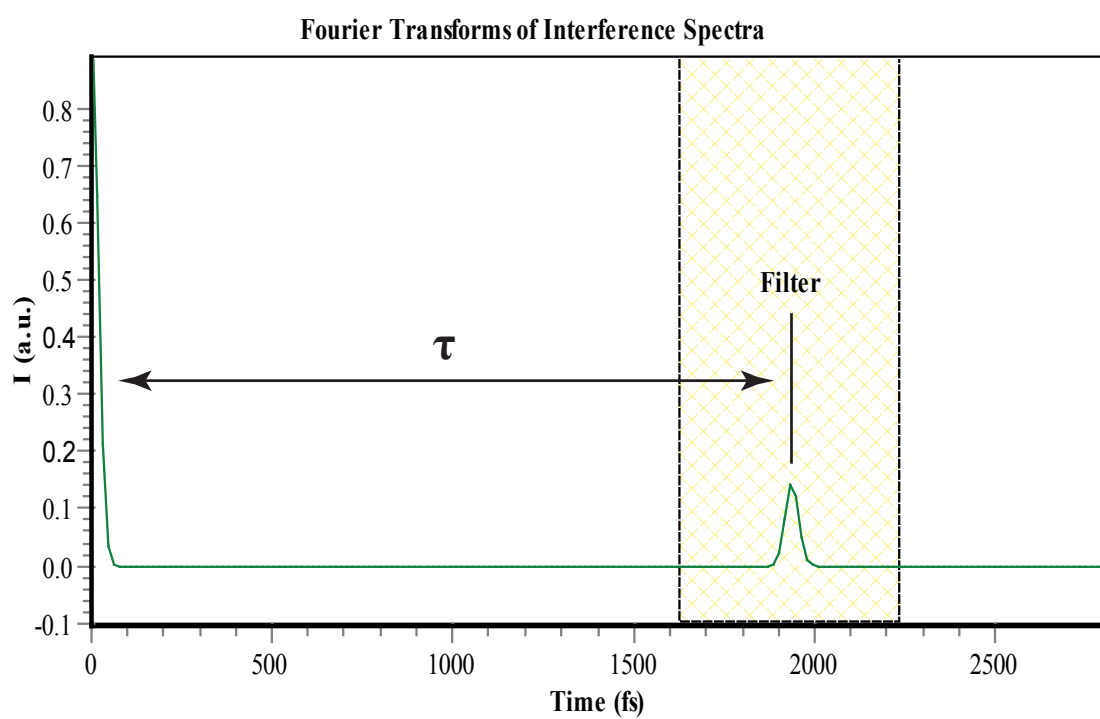
To extract the spectral phase from the experimental interferogram, we use a robust direct (noniterative) inversion procedure. This procedure is diagrammed schematically in Figure 3.3. The Fourier transform of the experimental interferogram from Figure 3.2 is shown in Figure 3.4. The component centered near  $t = +\tau$  is filtered and inverse transformed back into the frequency domain.



**Figure 3.3. Schematic diagram of the procedure for extracting the spectral phase from an interferogram.**

The next step of the phase reconstruction procedure is to remove the linear phase term  $\omega_c\tau$  from Equation 3.1. The most reliable method to do this is a direct measurement of  $\omega_c\tau$ . The spectrometer is calibrated by recording a spectral interferogram from the pulse pairs without imparting the spectral shear. In this case, the interfered pulses are identical and therefore the only phase contribution is  $\omega_c\tau$ . The linear phase obtained from the calibration is simply subtracted from  $\Phi_\omega(\omega_c + \Omega) - \Phi_\omega(\omega_c) + \omega_c\tau$ .

Once the linear phase is subtracted, we are left with the relative phase distribution  $\Phi_\omega(\omega_c + \Omega) - \Phi_\omega(\omega_c)$  between successive pairs of frequency components separated by  $\Omega$ . The spectral phase for a discrete set of frequencies separated by  $\Omega$  is constructed by concatenation. This inversion procedure is noniterative; that is, the phase is directly retrieved from the data by a series of linear transformations. Thus, given appropriate data, the reconstruction error associated with the inversion routine is zero. Of course the accuracy of the reconstruction is limited by the signal-to-noise ratio of the experimental data, as it is for all methods.



**Figure 3.4. Fourier transform of the SPIDERgram.**

## CHAPTER 4

### Apparatus Description

The optical scheme of Avoca-120 is shown in Figure 4.1. The direction of the horizontally polarized input beam is determined by the diaphragms D1 and D2. The reflections from the front and back sides of an uncoated fused silica etalon ET are used as the two time delayed replicas of the input pulse. The thickness of the etalon is 200  $\mu\text{m}$ , which produces a time delay  $\tau$  of approximately 2 ps between the two reflections. After the reflection by the two-mirror polarization rotator PR, the polarization of the replicas is changed from horizontal to vertical. Then with the help of steering mirrors M1, M2, M3 and the spherical Focusing Mirror FM ( $R = 200$  mm) the test pair of replicas is focused into the nonlinear crystal NC. Most of the input pulse passes through the etalon and diaphragm D2 into the grating stretcher. The stretcher consists of two diffraction gratings G1, G2 and a roof mirror RM1. The stretched pulse leaves the stretcher in the exact opposite direction from where it came, only higher so that it passes slightly above D2 and ET. It is then reflected by a steering mirror M4 and focused by the focusing mirror FM into the nonlinear crystal NC. The parallelness of the stretched beam and the test pair beam incident on FM is provided by appropriate adjustments of the M2 and M3 mirrors. These two beams should be parallel and lay in the same vertical plane with the highest possible accuracy. The optical path lengths of the stretched beam and the test pair beam from the etalon to the nonlinear crystal must be the same. The stretched beam path length can be adjusted with the delay line DL. Note: the stretched beam and the test pair beam are orthogonally polarized, so to up-convert the test pair with the stretched pulse a Type II 300  $\mu\text{m}$  KDP crystal in a non-collinear geometry is used. The NC is cut for phase matching at  $\lambda_o = 800$  nm and  $\lambda_e = 800$  nm ( $\theta \cong 70^\circ$ ) and is oriented so that the test pair of pulses is polarized along the ordinary axis of the nonlinear crystal. For this orientation of the nonlinear crystal, its bandwidth is considerably broader than when rotated through  $90^\circ$ .

The up-converted beam passes through lens L1, slit diaphragm SD, blue-green glass filter F2, and is focused by lens L2 (both lenses have a focal length of  $f = 60$  mm) at the entrance slit SL2 of the two-channel spectrometer. The input pulse spectrum is recorded by the same spectrometer. For this purpose, the zeroth order reflection of the input pulse from diffraction grating G1 is used. This reflection, with the help of the wedge W and two steering mirrors M6 and M7, passes through the entrance slit SL1. This beam can be attenuated with the neutral glass filter F1.

The two-channel diffraction grating (G1S 1200 grooves/mm, blazed for 800 nm) spectrometer allows us to simultaneously record the input pulse spectrum (in the wavelength range 740-860 nm) and the up-converted spectral interferograms (in the wavelength range 370-430). The recording of the spectra is carried out by two one-dimensional CCD arrays CCD1 and CCD2. Both CCD arrays have 3642 pixels with a pixel size of 8  $\mu\text{m}$  (W) x 200  $\mu\text{m}$  (H).

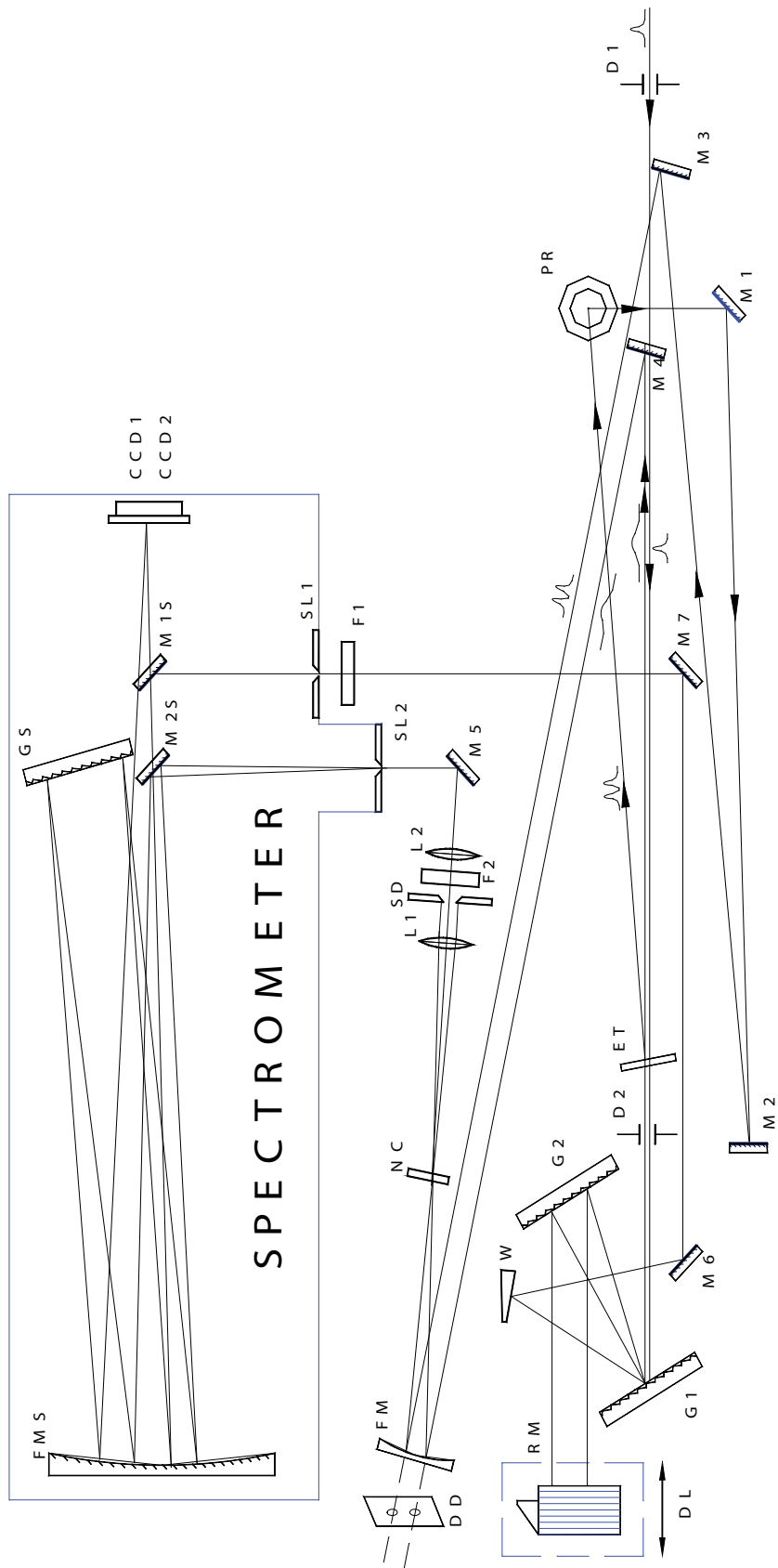


Figure 4.1. Optical schematic for Avoca-120.

## **CHAPTER 5**

### **Unpacking Avoca-120**

Carefully remove the device from the transportation box and very carefully mount it on your optical table. Use the height adjustable legs to mount the device. Make sure the device is level and at the beam height you need. Mount the device to the optical table with the supplied leg clamps. Lift the cover and carefully remove the transportation protector from the delay line micrometer MS (see Figure 5.1).

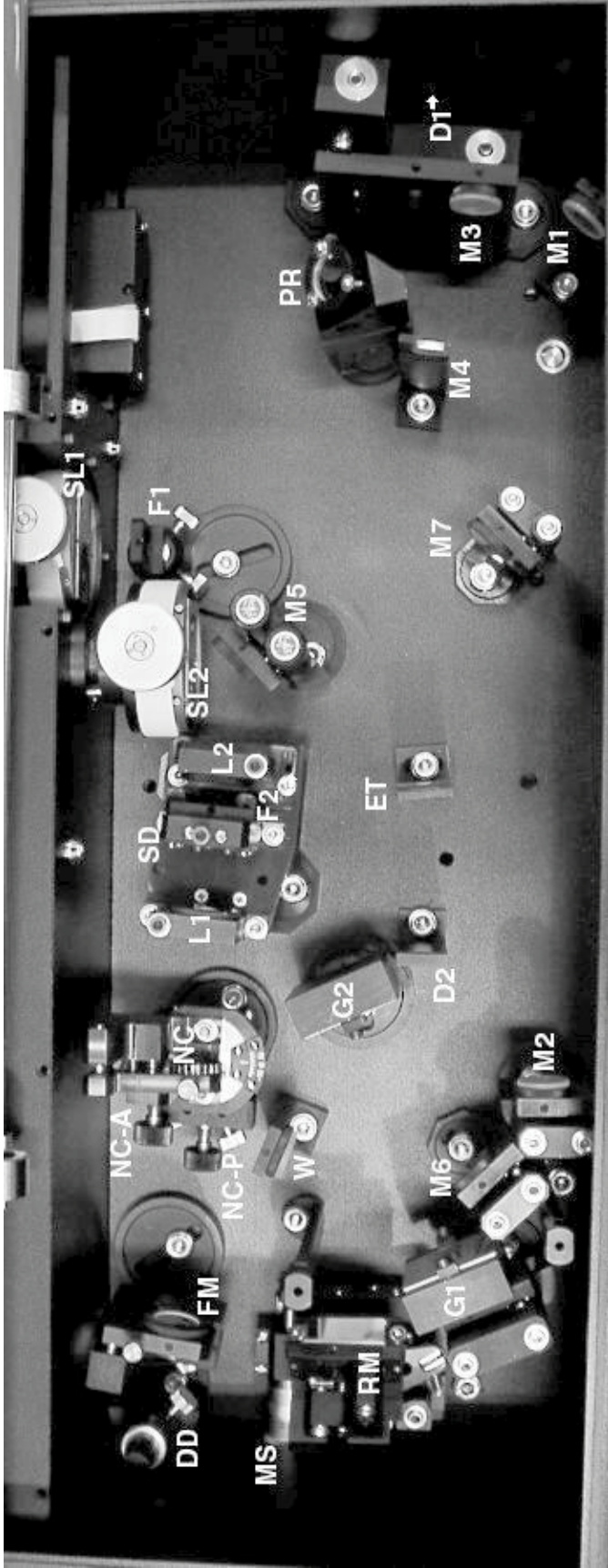


Figure 5.1. System schematic for Avoca-120.



## CHAPTER 6

### Device Installation And Setup

Efrat Software Installation and Configuration Notes

---

#### 6.1 REQUIREMENTS

- IBM PC compatible computer
- Processor > 600 MHz
- RAM > 128 MB
- HDD space for installation: 10 MB
- Video Display 1024x768 HighColor or better
- USB port
- Microsoft Windows 98SE/ME/2000/XP

#### 6.2 EFRAT SOFTWARE INSTALLATION

The software distribution consists of a `EfratSetup-3.1.2.0-Ormins-Ormins_1.exe` executable file and a set of files in the `Presets` folder. These files contain the information on spectral calibrations and sensitivity for the spectra registration system recorded during device manufacturing. The folder `Presets` must be in the same folder as the setup executable file.

##### **To install software:**

1. Run `EfratSetup-3.1.2.0-Ormins-Ormins_1.exe` by double-clicking it in Windows Explorer (if you have CD distribution and autoplay CD-ROM enabled then setup will start automatically after CD is inserted). On Windows 2000/XP you must have administrator privileges to install software. The Setup Wizard will guide you through the software installation process.
2. Select 'OrminsCCD USB (DUAL Head) DAQ Driver' item in the Components page of the Setup Wizard to install spectra registration CCD driver on your system.
3. The driver requires a vendor supplied operating system device driver to access data acquisition hardware through the USB interface. You should select 'Install OS driver' in the Additional Tasks page of the Setup Wizard to install the vendor supplied device driver. This will launch the vendor supplied Setup Wizard. You must use default settings proposed by the wizard and wait until it finishes its tasks. Select 'I want to restart my computer now' option from the Setup Finished page of the main Setup Wizard to complete software installation.

### **6.3 HARDWARE INSTALLATION**

1. Connect device to the computer using supplied USB cable.
2. Check that the device OrmisCCD appeared in the Device Manager under USB Controllers branch. In some cases Windows may try to reinstall OS driver and launch 'New hardware found' wizard. Follow the wizard and select the device driver found on the system.

### **6.4 DRIVER CONFIGURATION**

1. Launch Erat using Windows Start menu or desktop shortcut. The main window of the application will be opened.
2. Under 'Acquisition' menu choose 'Configure drivers...' item. The Driver List dialog box will be opened.
3. In Drivers List dialog box click the 'Add...' button. With the Open dialog box navigate to the folder where you have installed Efrat, and then to subfolder DRV\OrminsCCD. Select file named OrminsCCD.dll and click the 'Open' button. The OrminsCCD Configuration dialog box will be opened (the device must be connected to the computer at that time).
4. In the OrminsCCD Configuration dialog box you will see the device serial number and selected check box to the left of it. Just click the 'OK' button in this dialog box. Two spectra acquisition window will be opened.
5. Now you click 'Close' button in the Drivers List dialog box (or you will be unable to access the application main window).

### **6.5 LOADING SPECTRAL CALIBRATION**

1. In the spectra acquisition window 'Device:OrminsCCD<0>' (default name) click on the down arrow to the right of the 'Calibration...' button. Choose 'Load...' in the popup menu.
2. Navigate to the folder where you have installed Efrat and select the file named 'mainsp\_08\_130\_1.SCL'. Click the 'Open' button. Now you should have the appropriate spectral calibration loaded to that spectrum channel.
3. Repeat Steps 1 and 2 with the spectra acquisition window named 'Device:OrminsCCD<1>' but open the file named 'signalsp\_08\_130\_1.SCL'.

### **6.6 LOADING SPECTRAL SENSITIVITY DATABASE**

1. In the main window choose 'Sensitivity database...' under the 'Acquisition' menu.
2. Click the 'File' button and choose 'Merge...' item in the popup menu.

3. Navigate to the folder where you have installed Efrat and select the file named 'Spesens08\_130\_1.SDB'. Click the 'Open' button. Now you have the spectral sensitivity data loaded to the program.
4. In the spectra acquisition window named 'Device:OrminsCCD<0>' click on the down arrow to the right of the 'Equalization...' button. Choose 'Setup...' from the popup menu.
5. In 'Available Sensitivity Curves' list and select 'spsens08\_130\_1.SDB' and press the '>' button to move it to the 'Selected Sensitivity Curves' list. If the filter F1 is installed, add 'NF-9.SDB' as well. Click the 'OK' button to finish this procedure.

## 6.7 END NOTE

All settings you have made will be recorded in the program configuration file and will be restored when you launch Efrat again. For more information on the software operation see the Help files (available under 'Help' menu in the main window of Efrat) and other supplied documentation.

## CHAPTER 7

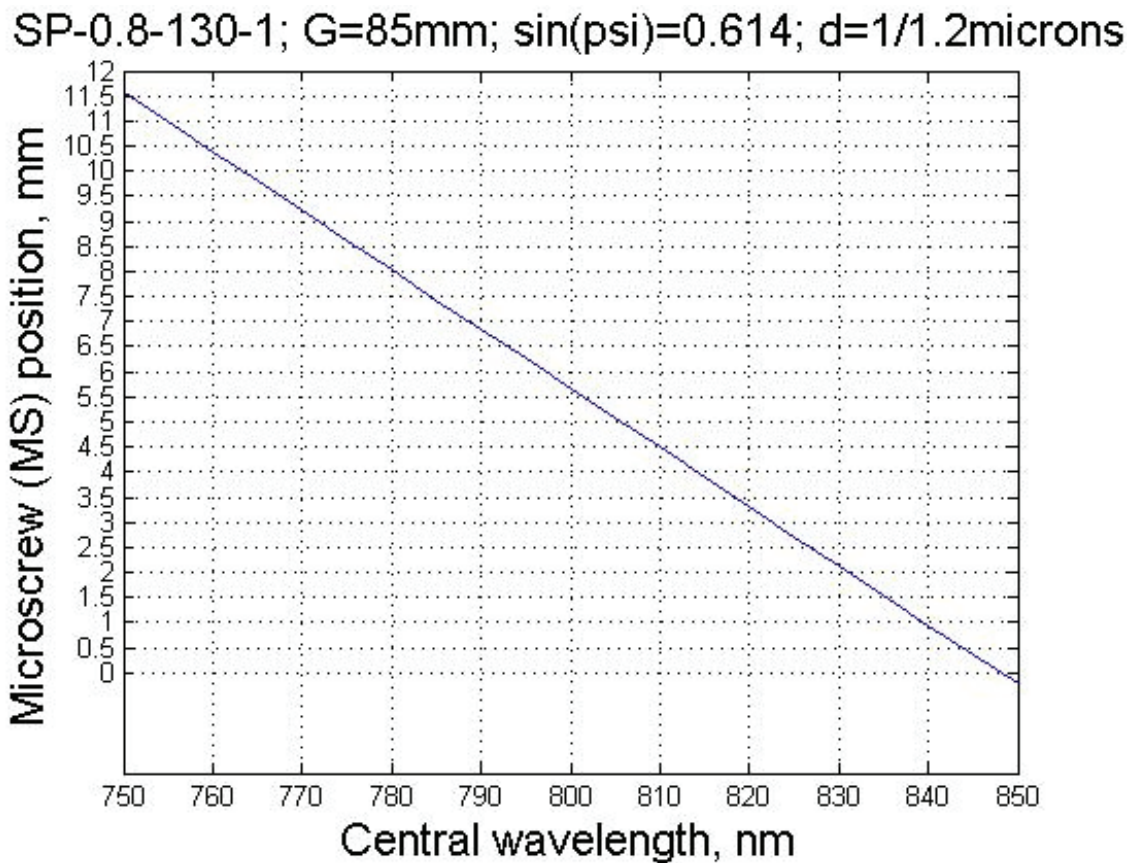
### Measuring Procedure

Before you start measuring pulses, please look through the Efrat Help files. You should also check the input pulse power. To make your first measurement easier, the average input power should be: 100-250 mW for a 100 MHz repetition rate beam, and 3-10 mW for a 1 kHz repetition rate beam. The beam diameter shouldn't exceed 4 mm (at  $1/e^2$  intensity level), though a 2-3 mm beam is preferable. Avoca-120 also expects a collimated beam without spatial chirp.

1. Steer the input beam through the installed flip diaphragms D1 and D2.
2. Flip down both D1 and D2. **Attention! Be careful when you flip down D2; make sure not to touch the etalon ET!**
3. Check the parallelness of the stretched and test pair beams. To do this, carefully flip down the focusing mirror FM in the horizontal position and let the two beams pass through the double diaphragm DD (see Figure 4.1 and Figure 5.1). Remove the side panel just behind DD and check the beam separation at a distance of 3-4 meters from DD. The beams should lay in the same vertical plane and the beam separation should be the same as at DD, approximately 8 mm. **Warning!** The stretched beam direction is factory maintained and should not need correction. Only change the alignment with mirrors M2 and M3.
4. Carefully flip the focusing mirror FM back to the vertical position.
5. Set the width of slit SL1 of the spectrometer to roughly 10-20  $\mu\text{m}$ . Turn on the 'Autorun' mode on the CCD<0> window of the Efrat software. Set the exposition time of the CCD to 50-100 ms and switch off the 'Equalization' button. Change the slit width and exposition time to set the input pulse spectrum in the 1000-3000 a.u. range. Block the input beam and zero the spectrometer using the 'Baseline' button. This correction should be carried out every time you run Efrat and after every exposition time change.
6. Loosen the adapter with the nonlinear crystal NC and rotate it to the position for recording the Reference spectrum. In this position the Red mark on the NC-adapter should be matched with the White mark on the NC mount. Tighten the adapter.
7. Set the width of the SL2 close to the middle position  $\sim 200 \mu\text{m}$ .
8. Translate the slit diaphragm SD so that only the test pair beam is allowed to pass, the lower beam spot after NC.
9. Check the maximum value of the CCD<1> signal (Reference spectrum). This signal should not be saturated. The saturation level is  $\sim 4000$  a.u.. If the signal is saturated, then slowly close SL2. Using mirror M5, try to get the maximal signal for the minimal

SL2 width. This maximal signal value should not exceed 3000-3500 a.u.. **Note**, the signal level also depends on the central wavelength of the input pulse spectrum. Since NC is factory phase matched for the central wavelength  $\lambda_c = 800$  nm, you may need to readjust if your center wavelength is different. To do this, use the nonlinear crystal adjustment knob NC-A. After optimizing the Reference signal level, record it to your Efrat reconstruction project.

10. Loosen the NC adapter and rotate it by  $45^\circ$  to the position for recording the SPIDER signal interferogram, or simply Signal as it is named in the Efrat software. In this position the White mark on the NC adapter should match with the White mark on the NC mount. Tighten the NC adapter again.
11. Use Figure 7.1 to set the delay line micrometer MS (see Figure 5.1) position according to the central wavelength of the input pulse spectrum.



**Figure 7.1. Delay line micrometer calibration position for center wavelength.**

12. Translate the SD so that only the noncollinear up-converted beam passes through it simultaneously blocking the stretched and test pair beams.
13. Optimize the Signal value by slightly adjusting mirror M5 and the SL2 width as is described in Step 9. Check the parallelness of the stretched and test pair beams by slightly adjusting only mirror M3 to maximize the Signal value. Then try to maximize

the Signal by small adjustments of NC as is described in Step 9. If the adjustments of M3 and NC are changed, it will be necessary to record the Reference signal again.

14. To reconstruct the input pulse you should enter in the Stretcher parameters. These are: Grating groove density - 1200 gr/mm, Grating separation distance - 0.085 m, and Input incident angle - 0.614 rad.
15. If the repetition rate of the tested laser is 10 Hz or less, you should use the outer synchronization of the CCD. To do this, connect the CCD synchronization port and the synchronization pulse source by means of the supplied cable marked by the arrows **from the synchronization source toward the CCD camera**. The synchronization pulse should be positive, 5-20 V in amplitude (the input impedance of the synchronization port is 11 k $\Omega$ ) and should precede the laser pulse by 1  $\mu$ s or more at the level 1-1.5 V. Another synchronization cable (**marked by arrows directed from the CCD camera**) should be used if for some purpose you need the CCD camera output synchronization pulse.

## REFERENCES

- [1] A. Zubov and T. I. Kuznetsova. *Laser Phys.*, 2, 1992.
- [2] V. Wong and I. A. Walmsley. *Opt. Lett.*, 19, 1994.
- [3] C. Iaconis and I. A. Walmsley. *Opt. Lett.*, 23, 1998.
- [4] C. Iaconis and I. A. Walmsley. *IEEE J. Quantum Electron.*, 35, 1999.