

## BARCOS, an automation and remote control system for atmospheric observations with a Bruker interferometer

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In order to make long-term monitoring of the atmospheric composition using commercial Bruker Fourier transform spectrometers more cost effective, a system called BARCOS has been developed. The system enables one to perform the operation of the spectrometric atmospheric observations in a remotely controlled or autonomous way, without human presence at the measuring site. Several observation geometries are foreseen, including solar and lunar absorption spectrometry. BARCOS is built using existing commercial hardware and software components, including the Bruker software for the operation of the spectrometer (OPUS) and runs in a personal computer (Microsoft) environment. It includes a small meteorological station. It is a flexible system, allowing manual interventions at any time. To run BARCOS effectively, the only prerequisite is that internet access is available at the site of operation. This article describes the BARCOS system hardware and software configurations. © 2007 American Institute of Physics. [DOI: 10.1063/1.2437144]

### I. INTRODUCTION

The operation of Fourier transform infrared (FTIR) spectrometers for the monitoring of the chemical composition of the atmosphere by solar absorption measurements is costly in terms of manpower, especially if the instrument is located at a remote site. Still there is a strong demand to increase the number of such observations and to have them take place at sites that are more difficult to access, for example, at high altitude, in the tropics, at uninhabited locations, etc. In particular, the Network for Detection of Atmospheric Composition Change (NDACC, formerly called NDSC, Network for Detection of Stratospheric Change, <http://www.ndacc.org>)<sup>1</sup> has a nonuniform spread of observatories, with a larger concentration in the northern hemisphere and in the United States, and lacks observatories in the tropics, in Africa and Asia and the southern hemisphere. At many locations, FTIR observations are carried out on a campaign basis, because of the lack of available manpower to run the instruments continuously.

Therefore to acquire more observations in a more cost-effective way, it is of great interest to develop systems to run such instruments in a remote-controlled and/or autonomous mode. Such a system has been developed to control the automatic operation of a Bruker Fourier transform spectrometer (FTS) for performing atmospheric solar absorption measurements. It is called BARCOS which stands for “Bruker automation and remote control system” for atmospheric observations’, and is described in this article. It has been implemented successfully during FTIR campaign observations at Ile de la Réunion (21 °S, 55 °E) in October 2002 at

the high mountain site of Piton du Maito [2200 m above sea level (asl)] and in September to October 2004 at the university campus at Saint-Denis (Fig. 1).

This article is organized as follows. Section II outlines the general working principle of BARCOS. Sections III and IV describe the hardware and software components, respectively, while Sec. V provides a short view on BARCOS remote control capabilities.

### II. WORKING PRINCIPLE

The entire BARCOS observatory can be controlled by software from one master personal computer (PC). The only requirement is that for every observation day a corresponding script can be found in the master PC. At the beginning of each day, BARCOS will search for this script and execute it. A script contains a list of commands, each carrying a tag. The tag can be either the time or the solar zenith angle at which the command has to be executed.

Before and during the execution of any BARCOS script line, a set of external parameters (carefully selected by the

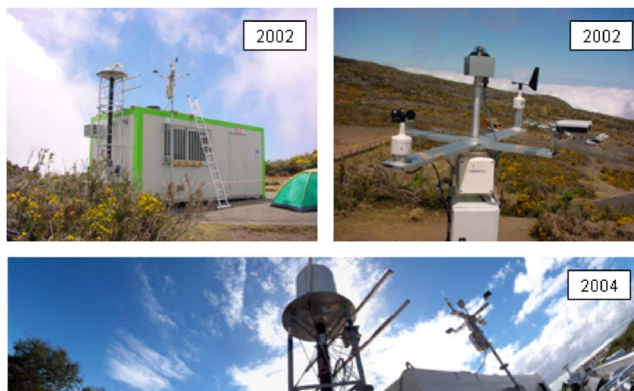


FIG. 1. (Color online) Ile de la Réunion campaigns.

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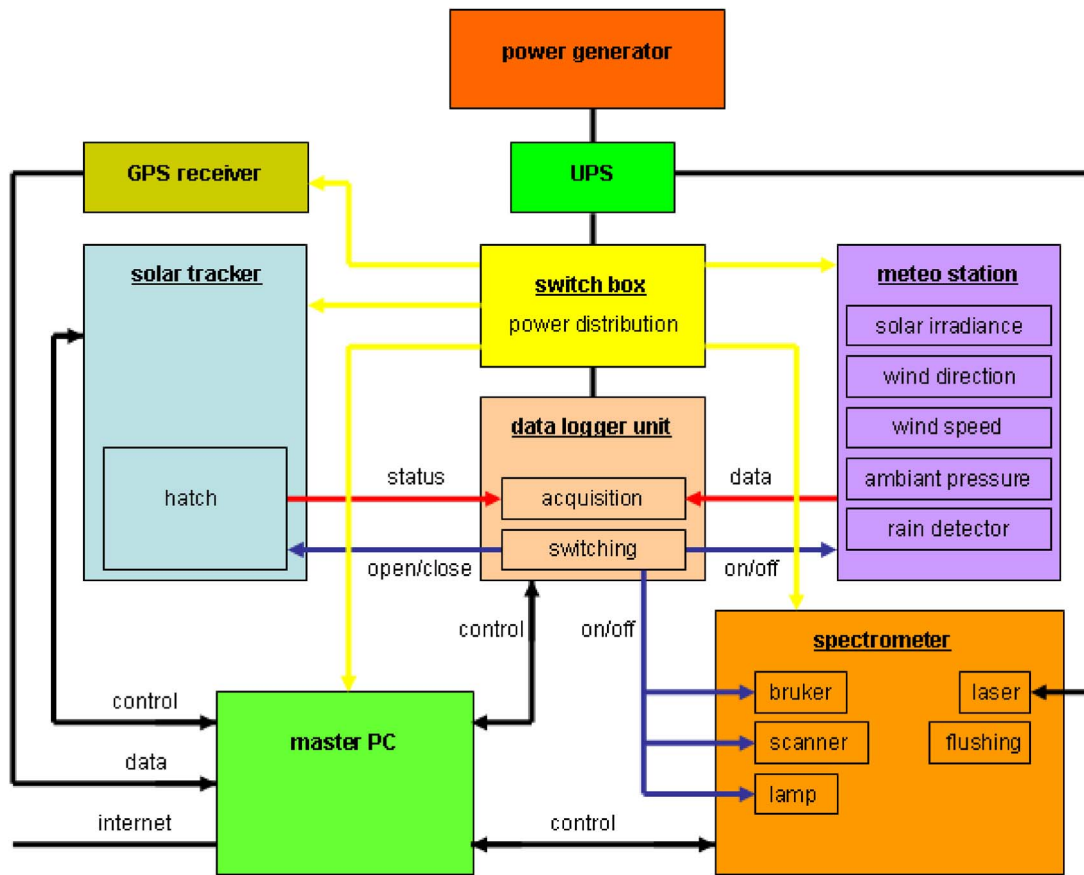


FIG. 2. (Color online) General hardware scheme.

operator) is checked and interpreted in order to take decisions on whether to start, interrupt, or stop a measuring sequence.

Using scripts eases the instrument control from a remote location. New scripts can be uploaded (or existing ones can be modified) at any time. The ultimate solution for remote control is to mirror the master PC's peripheral access (keyboard/mouse/screen) to a remote PC, provided that a high bit rate internet link between the measuring site and the remote user's desktop is available.

Although a high degree of automation is aimed for, the possibility to manually control the instrument remains present at all software levels through user-friendly graphical interfaces. Data storage and status logging are supported following a strict file directory structure.

### III. HARDWARE COMPONENTS

The entire BARCOS system is run from one master PC which contains the electronic boards that are specific of the four hardware components (spectrometer, solar tracker, meteorological station, and data logger unit) (Fig. 2). Furthermore the master PC is equipped with a dual display graphics adapter, enabling the simultaneous use of two displays for a better graphical representation of the various interfaces. The whole system is powered from mains or from a power generator through an uninterruptible power supply.

#### A. The spectrometer

The central part in the BARCOS setup is the IFS120M Bruker spectrometer (with its associated electronic box and acquisition card in the master PC), including the spectrometer scanner, the laser, an external lamp, and a flushing device.

Detectors for midinfrared applications must be cooled to liquid nitrogen temperature. The filling of the associated detector dewars with liquid nitrogen ( $\text{LN}_2$ ) is done automatically using a self-contained  $\text{LN}_2$  microdosing system. The filling is initiated based on an internal timer and stopped when level sensors in the detector dewars indicate that they are full.

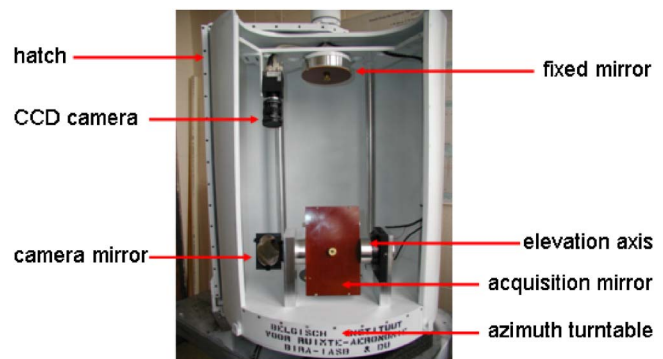


FIG. 3. (Color online) BARCOS solar tracker (University of Denver and Belgian Institute for Space Aeronomy).

## B. The solar tracker

The second key element in the setup is a solar tracker built at the University of Denver and modified at BIRA-IASB (Fig. 3).<sup>2</sup> It provides stepper motor driven azimuth and elevation control based on the guidance of a sensitive charge-coupled device (CCD) camera. The solar tracker is accompanied by two electronic boards to be installed in the master PC, one for the image acquisition and another one for the control of the stepper motors.

Azimuth and elevation control are provided by two high-precision stepper motors, driving both the main acquisition mirror, which directs the light to the Bruker spectrometer, and a secondary mirror, the movement of which is bound to that of the main mirror, but which directs part of the incoming light to a tracking camera. The azimuth motor is mounted on a fixed base plate from where it drives a horizontal turntable. This table supports (a) the acquisition mirror, which is mounted around a horizontal axis that is driven by the elevation motor, and (b) a mechanical structure, to which a hatch is attached that can close off the interior of the tracker hermetically. The light reflecting from the acquisition mirror is directed to a fixed mirror at the top of the tracker, and from there it is directed vertically downwards through a central opening in the turntable and the base plate. Since the line of sight towards the Sun (or any other target light source in the sky) must not be hampered by buildings, trees, etc., the solar tracker is mounted on a platform on top of a 4 m high tower, at the foot of which the vertical light beam coming out of the solar tracker is reflected into the spectrometer (inside a building or container) by an adjustable flat mirror mounted at 45°.

A smaller secondary mirror directs rays of the target light source towards a sensitive high resolution (1300 × 1030 pixels) high speed CCD camera. The position of the target's image on the camera is used for fine servocontrol of the stepper motors. Due to the camera's high sensitivity and the fine motor stepping, the device is capable of tracking not only the Sun but also much weaker or smaller light sources, such as stars and the moon, with a pointing precision of 0.2 arc sec over an angular excursion of 355°.

At the entrance of the spectrometer a small fraction of the light beam is focused on a four quadrant detector. The output currents of its four quadrants are a measure for the incident light intensity. Equal currents on the four quadrants indicate a good tracking of the Sun. Whereas the four quadrant detector is currently used for passive monitoring of the solar tracking performance, it will be used in a later stage for actively driving the solar tracker motors, assisting, or even replacing, the solar tracker camera.

The solar tracker has a cylindrical enclosure that is fixed to the azimuth turntable. A segment is cut out in the enclosure to provide an opening to the acquisition mirror assembly and the fixed mirror. The enclosure can be closed by a hatch that is controlled by a pneumatic system, independent of the solar tracker movements. Two magnetic switches (magnets incorporated in the piston and reed contacts mounted on the piston housing) indicate the "closed" and "opened" positions of the hatch.

The solar tracker is controlled from the master PC through a stepper motor control board interfacing with a two

axes stepper motor power drive for the azimuth and elevation stepper motors and a camera image acquisition board (frame grabber).

## C. The meteorological station

A third major component of the BARCOS system is a small meteorological station including commercial sensors for the measurement of wind direction (Lambrecht), wind velocity (Lambrecht), local ambient pressure (Lambrecht), direct solar irradiance (Soni), and the detection of precipitation (Lambrecht).

## D. The data logger unit

Finally, BARCOS includes a data logger with an extended number of input channels (40) for the acquisition of meteorological and housekeeping data and a series of output channels (20) for on/off switching of the above mentioned BARCOS devices (subsystems and sensors). The exchange of housekeeping information and switching commands between the master PC and data logger unit passes over a GPIB link. Additional components of BARCOS are a GPS receiver for updating the PC time on a daily basis and a switching box including electronic protection circuitry, low voltage power supplies, relays, power consumption control, and cable routing.

## IV. SOFTWARE CONFIGURATION

On the master PC four independent software modules run in parallel: (1) OPUS4.0, Bruker's data acquisition and processing software; (2) the master module (MASTER VI), responsible for the central management of the system; (3) the housekeeping module (HSK VI), gathering meteorological and instrument surveillance data; and (4) the solar tracker module (DST VI), driving the solar tracker. The latter three modules have all been developed in LABVIEW6.1 (VI stands for virtual interface). The design of the software takes advantage of the multiple possibilities to communicate internally between LABVIEW VIs and of the elegant dynamic data exchange (DOE) communication protocol that is available in both LABVIEW and OPUS. A schematic overview of the software configuration is shown in Fig. 4.

A particularly attractive feature in LABVIEW is the possibility to use global variables that are known in all VIs running in the actual working environment. If a global variable adopts a value in one VI, all other running VIs have immediate access to that value.

The start up time and operation time of the above-mentioned four main BARCOS software modules (MASTER VI, HSK VI, DST VI, and OPUS) can be scheduled using the WINDOWS TASK SCHEDULER of the master PC. For safety reasons the BARCOS equipment can be switched off fully automatically (e.g., during the night). All systems can be powered off and all software modules contain programable timers to terminate the execution of the module. All running programs close themselves using the WINDOWS TASK SCHEDULER. Only the master PC and the data logger will remain powered on at any time such that the task scheduling is automatically resumed every day at a specified time.

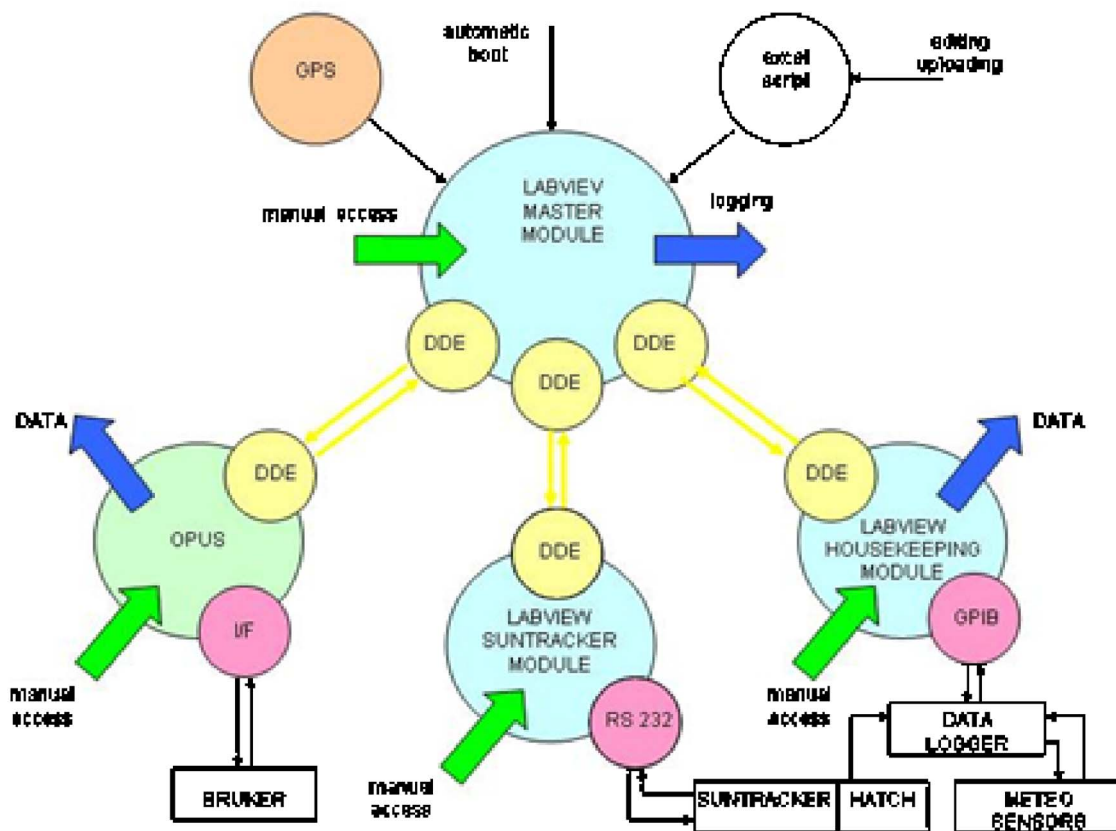


FIG. 4. (Color online) General software scheme.

### A. The master module

The automatic operation of the Bruker spectrometer, the solar tracker, and the housekeeping system is coordinated in a LABVIEW written master module (MASTER VI).

In the MASTER VI a dedicated protocol is set up for the communication with the two other LABVIEW VIs (HSK VI and DST VI) based on the principle of global variables. Each communication link (MASTER-HSK and MASTER-DST) uses a set of three global variables, one containing the command itself, a second being the “sent” flag (set as soon as the MASTER VI has sent a command), and a third being the “executed” flag (set when the command has been executed by the HSK VI or the DST VI). This protocol allows not only to pass commands from one VI to another, it also synchronizes the commands on one link.

The only software module that cannot be communicated with through global variables is OPUS. OPUS, however, supports the DDE protocol, which is also supported in LABVIEW through a number of preprogrammed VIs in its interface library. Using DDE a server-client relationship can be established between the two software modules.

The managing task of the MASTER VI is twofold. First it has to make sure that the solar tracker is always protected against bad weather conditions. Second it has to check whether it is safe and scientifically useful to send a command to a subsystem, and more specifically to OPUS. The required management information from the housekeeping and solar tracker modules is provided in a number of system parameters. Before passing any command to a module, the MASTER

VI checks if the housekeeping module has detected any unfavorable environmental condition. If that is the case the command will not be sent.

The master must schedule the measurements, i.e., to start, stop, and/or interrupt measurements at the appropriate times, taking into account some predefined measurement conditions. Therefore it passes commands towards the different control modules (OPUS, DST VI, and HSK VI) and retrieves and interprets information returned from these modules. Before passing a command to OPUS, the MASTER VI not only checks whether an unfavorable environmental condition exists but also verifies with the solar tracker module whether the solar tracker is actually in the desired state (tracking the Sun), and if the direct solar irradiance is higher than a predefined threshold level (“go” condition). During a measurement, the MASTER VI will immediately close the hatch of the solar tracker and kill any running OPUS task, whenever it receives a “no go” warning from the housekeeping module.

The scheduling of the measurements is implemented using an elementary scripting language. Scripts are text files containing lists of BARCOS commands. The automatic operation of BARCOS is based on the existence of a “script of the day” that contains all the commands to be issued during one complete measuring day. Each command carries a time or a source (Sun, moon, etc.) zenith angle tag, indicating when that command should be executed, and a destination tag, indicating the module to which the command should be sent (OPUS, DST, or HSK) or indicating that another script must be called.

When the daily script has been found or when a script has been selected manually, it will be copied line by line from the script file into the program's execution table, checking in real time if the script contains calls to other scripts. If so, the lines of the "subscript" are inserted immediately in the execution table, resulting in a list of elementary commands for the DST, HSK, and/or OPUS modules.

During the transfer from the script file to the execution table, zenith angle tags (if present) are converted into time tags using daily source ephemeris calculations, so that finally the execution table contains the exact time each command has to be executed.

The table is then executed line by line. When the GPS driven system time matches the time tag of a command line, the contents of that line (base field plus optional parameter fields) are sent to the subsystem indicated in the destination field. This is repeated until the end of the script is reached. Lines with a time tag equal to 99.99 are executed immediately following the previous command, regardless of the system time. All actions of the MASTER VI are recorded in a daily electronic logbook.

## B. The housekeeping module

The main purpose of the HSK VI is to interrogate a set of housekeeping channels on a regular time base. These channels gather both meteorological data (collected in a small meteorological station) and status information about the different subsystems. Some examples of the environmental parameters and instrument statuses that are probed are ambient pressure, wind direction and velocity, occurrence of rain, direct solar irradiance, temperature and humidity inside the spectrometer, four quadrant detector signals indicative of spectrometer alignment, power consumption of subunits, hatch open/close indication, voltage of power supplies, etc.

Collecting one complete set of housekeeping data is called "a scan." The repetition rate of the scans and their contents (which channels are probed) can be chosen by the user. After conversion into real physical values, the logged data are displayed on screen and stored in memory.

Since the purpose of BARCOS is to operate in an automatic mode, it is crucial to have the information about the housekeeping parameters. Some of them are used by BARCOS to decide whether to continue or to stop measurements (e.g., presence of clouds makes measurements useless, precipitation or heavy wind can endanger the instrument, an elevated temperature inside the instrument must be avoided, etc.). If one of the housekeeping conditions becomes threatening for the correct operation or the safety of the instrument, this must be signalled to the MASTER VI. Therefore the HSK VI sets with each scan a flag (system parameter GONOGO) that indicates if measurements can be continued or must be stopped. This flag is known at any time in the MASTER VI. The user can select the housekeeping values that he wants to consider in the setting of the GONOGO flag. He can also specify their lower and upper threshold values as well as the number of consecutive mismatches that must have occurred before the GONOGO flag flips from "go" to "no go" condition.

Besides the crucial GONOGO flag, three other house-

keeping values are made available to the MASTER VI as system parameters: MISMATCH (the parameter that caused the GONOGO flag to switch to the "no go" condition), SUN (direct solar irradiance in  $W/m^2$ ), and HATCH\_STATUS (hatch open, hatch closed, or hatch moving).

The second purpose of the HSK VI software is to provide the possibility to power on (or off) a device or subsystem, by activating (or deactivating) a switch line in the data logger, which closes (or opens) the corresponding relay in the electronic switch box, so that power is fed into (or cut off from) the appropriate device or subsystem.

The complete functionality of the HSK VI can be controlled manually from a graphical interface or from BARCOS scripts. Four basic types of HSK commands exist: scanning, switching, configuring, and threshold setting commands.

## C. The solar tracker module

An image acquisition software, IMAQ, is used for handling the CCD data frames from the solar tracker's camera. A motion control software, FLEXMOTION, is implemented for performing in real time two axes simultaneous coordinated motion control of the stepper motors. Both the image acquisition and the motion control programs are addressed through dedicated LABVIEW VIs. These VI's are embedded in one overall LABVIEW module that controls the complete functionality of the solar tracker (DST VI) and run in parallel to the master and housekeeping modules and the OPUS program.

In the graphical user interface of this solar tracker module all parameters can be set, working modes selected, and the complete camera image is displayed and updated continuously.

The solar tracker module has four different working modes.

- One point mode, in which the tracker is pointed to a fixed position in the sky which can either be specified as  $(\varphi, \theta)$  ( $\varphi$ =azimuth angle,  $\theta$ =elevation angle) or as

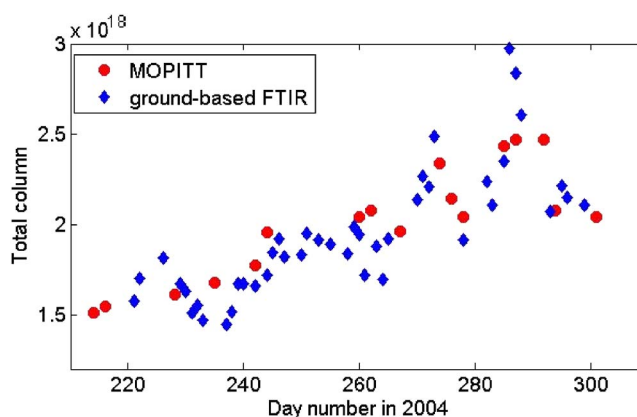


FIG. 5. (Color online) Time series of total column abundances of CO (in molecules/cm<sup>2</sup>) observed by FTIR ground-based measurements during the 2004 campaign at Ile de La Réunion (blue diamonds), in comparison with overpass data from the MOPITT experiment on the Terra satellite (red circles).

( $X, Y$ ) ( $X$ =number of azimuth motor steps from home position,  $Y$ =number of elevation motor steps from home position).

- Calculated mode, in which the solar tracker follows the calculated trajectory of the Sun even when the sky is completely covered. PC time and latitude, and longitude and time zone of the instrument's local position are used to calculate the number of motor steps ( $\Delta X, \Delta Y$ ) needed to go from the "actual" to the "next" position. Fine tuning of the conversion formula has to be done during instrument alignment.
- Tracking mode, in which the solar tracker starts by scanning a segment of the sky (defined by the user) in order to locate the Sun. As soon as the Sun is found, the solar tracker keeps the solar disk centered on the camera. The drift of the solar center from the center of the camera, expressed in motor steps ( $\Delta X, \Delta Y$ ), is constantly fed back to the stepper motors so that the tracker is permanently locked on the Sun (until the solar image disappears at sunset or due to clouds). The solar tracker module contains a number of image processing blocks that allow the definition of a unique contour of the solar image (particle recognition). They are based on user definable threshold levels (upper saturation and lower noise limits) for the camera image pixel values. The solar tracker module will track only when exactly one contiguous "particle" is recognized.
- Automatic mode combines the calculated and the tracking mode. It is the preferred mode when the instrument has to work without human assistance. It starts up with a procedure to search the Sun in the region around the theoretically calculated position. Once the Sun is found, its image is tracked as long as it is recognized. When the Sun is "lost" the mode switches to "calculated mode," when the Sun reappears the tracking mode is adopted again, and so on.

While tracking a light source (tracking mode or automatic mode) the solar tracker will move to a new position as soon as the drift of the center of the solar image from the desired position on the camera's field of view has become higher than a user-defined number of azimuth motor steps and elevation motor steps. Setting these numbers too high would result in a nonsmooth tracking behavior, while setting them too low would make the solar tracker's behavior too "nervous."

The operator may wish to take measurements only when the target light source is correctly tracked or, for some reasons, he may also want to operate when the tracker follows the calculated route. Therefore global variables "TRACK" and "CALC" can be enabled or disabled in the solar tracker module, depending on whether the solar tracker is in the tracking mode (or in the tracking section of the automatic mode), hence locked on the target light source, or whether it is in the calculated mode (or in the calculated section of the automatic mode), respectively. These global variables are then interpreted in the master module which will start a measurement only when these global variables correspond to the operator's wish.

All solar tracker commands can be implemented from a BARCOS script as well as manually from the graphical interface.

#### D. The spectrometer section

The spectrometer section of BARCOS is constituted mainly of Bruker's user software package OPUS (Version 4.0). In order to integrate OPUS in an automatic procedure the direct manual access to OPUS (still supported in BARCOS) has to be replaced by a communication protocol between MASTER VI and OPUS using a DDE link. Through the DDE link any OPUS command can be sent from a BARCOS script.

When OPUS is operated manually, the measurements are defined in the so-called "measurement files" (.xpm files). Herein, a number of optical settings of the Bruker spectrometer must be defined, including the optical aperture (APT), as well as the detector preamplifier gain (PGN), and ADC conversion or signal gain (SGN). For a specific type of measurement, the settings of the latter two parameters will strongly depend on the environmental and meteorological conditions. PGN and SGN must be optimized to have a maximum, nonsaturated, signal. If the signal still saturates with minimal gain values, then one may reduce the APT to avoid saturation.

When working in an automatic mode, these settings must be determined autonomously by the controlling software. Therefore, an automatic gain control macro has been written in OPUS that can be called from a script through the DDE link.

#### V. REMOTE CONTROL

Efficient exploitation of the high degree of automation in BARCOS requires easy access to the system from a remote location. This implies that wherever BARCOS is installed a connection to the internet has to be available. Since measurement campaigns are often set up at remote or difficultly accessible sites where wired access to the internet is not always assured, BARCOS can be equipped with a Nera World Communicator, offering the possibility to communicate wireless virtually anywhere in the world. This satellite phone provides a portable 64 kbps ISDN communications service for data and voice transmissions via inmarsat geostationary satellites, hooking up BARCOS' master PC easily to the internet.

Remote control to BARCOS can range from establishing a common telnet or ftp connection to the master PC and uploading new scripts or downloading registered data files, up to emulating the complete graphical BARCOS interface (such as it runs on the master PC) on a remote user's PC on the user's desktop by means of virtual network computing (VNC).

VNC software makes it possible to view and fully interact with one computer from any other computer or mobile device anywhere on the internet. VNC software is cross platform, allowing remote control between different types of computer. For ultimate simplicity, there is a JAVA viewer, so that any desktop can be controlled remotely from within a browser without the need to install software.

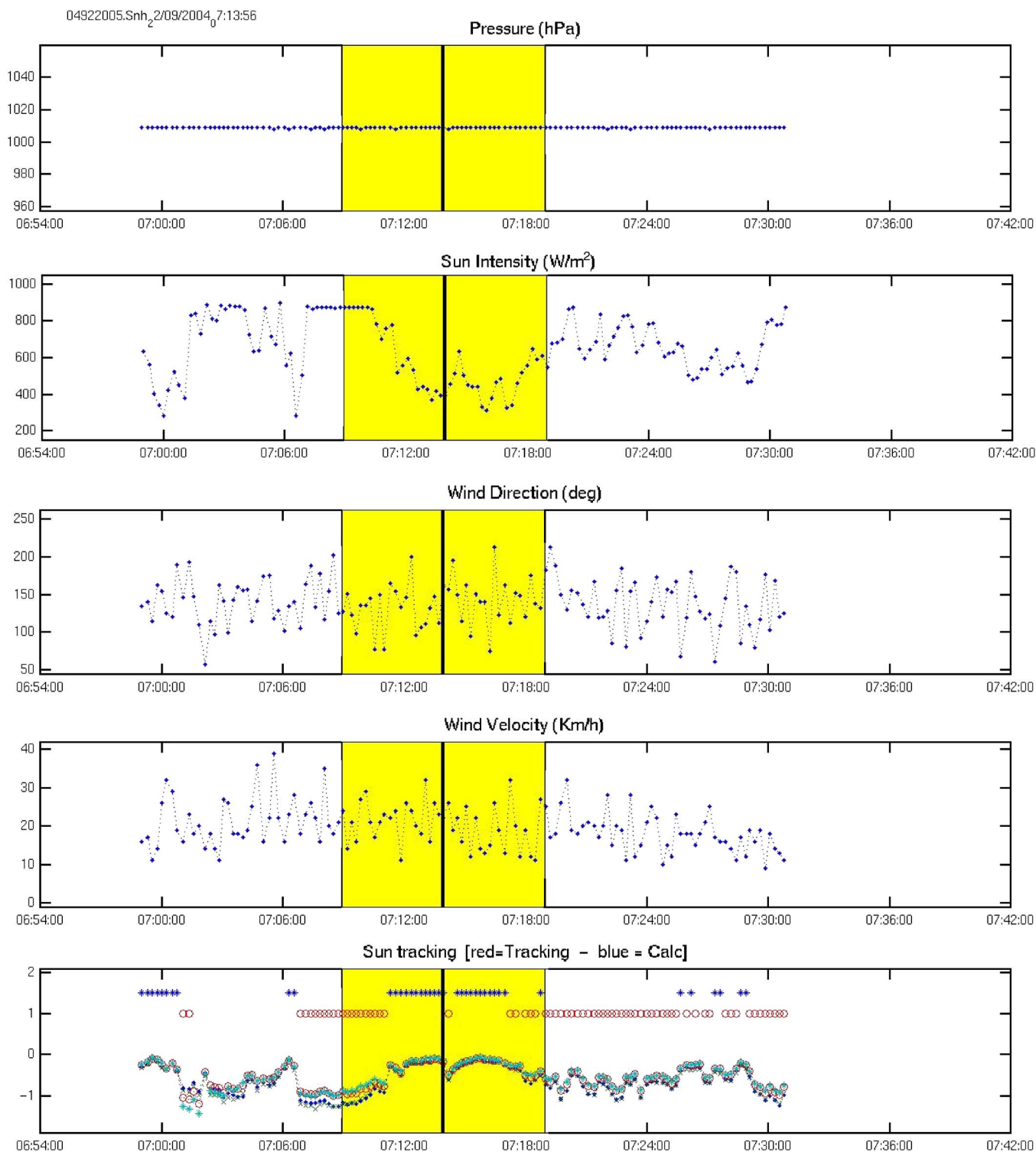


FIG. 6. (Color online) Meteorological data logged in BARCOS at Ile de la Reunion on September 22 2004 between 7:00 and 7:30 UT. From top to bottom, as a function of time (UT): local pressure (hPa), sun intensity ( $W/m^2$ ), wind direction (degrees), wind velocity (km/h), and sun tracker status. The status of the sun tracker in the bottom graph is represented both by a toggle switch (red: tracking mode; blue: calculated mode) and by the four output signals of the four quadrant diode detector (green, blue, cyan, and red symbols)

## VI. DEMONSTRATION OF BARCOS

A first version of the BARCOS system has been used during a campaign for FTIR measurements at Piton du Maïdo (Ile de La Réunion), in October 2002. The final BARCOS system, as described in this article, was used to operate the instrument during a campaign performed at the university

campus of St. Denis (Ile de La Réunion), from August till October 2004. BARCOS performed reliably throughout both campaigns. For security reasons and because automatic liquid nitrogen filling was not implemented yet, there was always one operator at the site. In the near future (2007), a new campaign, lasting several months, is planned, during which

the system will operate automatically without a permanent operator, while keeping the remote control option for verification and possible interventions in the case of failure or modifications in the planning of the observations.

Figure 5 shows the time series of total column amounts of carbon monoxide observed during the 2004 campaign. The data are in very good agreement with correlative data from the measurement of pollution in the troposphere (MOPITT) experiment. They show the seasonal rise of CO in the southern tropical regions in local spring which may be attributed to the cross-equatorial transport of CO from the northern hemisphere. Enhancements on October 12 and 13 are due to advection of biomass burning emissions over Madagascar.

Before processing the spectra, a careful inspection of the data quality is made, using the housekeeping data, in particular, the meteorological data. Figure 6 shows meteorological data logged in BARCOS during the recording of a spectrum; the exact duration of the spectral scan is highlighted in yellow. In this example, recorded on September 22 2004 at about 7:15 UT, the variation of the solar intensity was so large that the tracking was lost. In the bottom graph it is seen that the tracker switched from tracking mode to calculated mode. Therefore, in this case, the corresponding spectrum was rejected.

## VII. DISCUSSION

BARCOS is a system that complements a Bruker FTS with a sophisticated solar tracker, a self-contained liquid nitrogen filling system, and a versatile meteorological station, while adding to it a software implementation that enables the control of all system components in an integrated way. The

software is written in LABVIEW6.1 and uses a simple scripting language. The whole system is commanded from a single master PC.

BARCOS has been designed such as to be capable of making high performance FTS measurements with a high degree of instrument safety and autonomy at any location. It offers a user-friendly graphical interface, allowing manual access (commanding) at any time and providing a clear presentation of the scientific data as well as environmental and instrumental monitoring data.

The advantages of using BARCOS are obvious: once the system is set up at a given location and the optical alignment has been done, it can be run in an automatic mode, as long as daily scripts are available on the master PC. If the master PC is connected to the internet, remote control can be performed.

BARCOS enhances significantly the cost effectiveness of FTS measurements at a remote location and thus has the potential of facilitating long-term monitoring activities.

## ACKNOWLEDGMENTS

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<sup>1</sup>M. J. Kurylo and S. Solomon, NASA Report No. 19930047397, 1991 .

<sup>2</sup>T. Hawat, T. M. Stephen, M. De Mazière, and E. Neefs, Proc. SPIE **5082**, 13 (2003).