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Authors	MARONGIU, MARCO, PELLIZZONI, ALBERTO PAOLO, BACHETTI, Matteo, MULAS, Sara, RIGHINI, SIMONA, MURTAS, Giulia, LORU, SARA, EGRON, ELISE MARIE JEANNE, IACOLINA, Maria Noemi
Affiliation of first author	O.A. Cagliari
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A dedicated pipeline to analyse solar data with INAF radio telescopes: SUNPIT (SUNdish PIpeline Tool)

Marco Marongiu[1], Alberto Pellizzoni[1], Matteo Bachetti[1], Sara Mulas[2,3], Simona Righini[4], Giulia Murtas[5], Sara Loru[6], Elise Egron[1], Maria Noemi Iacolina[3]

[1] INAF - Osservatorio Astronomico di Cagliari,
Via della Scienza 5 - 09047 Selargius (CA), Italy

[2] Dipartimento di Fisica, Università degli Studi di Cagliari,
SP Monserrato-Sestu, KM 0.7 - 09042 Monserrato (CA), Italy

[3] ASI - c/o Osservatorio Astronomico di Cagliari,
Via della Scienza 5 - 09047 Selargius (CA), Italy

[4] INAF - Istituto di Radioastronomia,
Via Gobetti 101 - 40129 Bologna, Italy

[5] College of Engineering, Mathematics and Physical Sciences,
Harrison Building, StreathamCampus, University of Exeter,
North Park Road, Exeter, EX4 4QF, UK

[6] INAF - Osservatorio Astrofisico di Catania,
Via Santa Sofia 78 - 95123 Catania, Italy

Abstract

This technical note describes SUNPIT (SUNdish PIpeline Tool) – the pipeline aimed at the imaging procedure and the data analysis of the radio solar data – and guides the user to properly reduce and analyse the solar data. SUNPIT is designed for radio data acquired with some radio telescopes of the INAF Network: the Sardinia Radio Telescope (SRT), and the Medicina Radio Telescope. The present user manual follows the development of software for solar imaging and data analysis of Active Regions (ARs), performed in the framework of the INAF Proposal "SunDish Project" (PI: A. Pellizzoni). This project has been active since 2018 with the goal of monitoring the solar atmosphere at high radio frequencies (at present 18 – 26 GHz) through single-dish observations.

These solar observations will be enhanced through the upgrading of SRT with the new cryogenically cooled receivers, including a 19-feed in Q-band (33 – 50 GHz) and a 16-feed in W-band (75 – 116 GHz), in the context of the National Operative Programme (Programma Operativo Nazionale-PON); this project will provide in the near future an upgrading with the new receivers up to 116 GHz also for the Medicina and Noto Radio Telescopes, to provide the scientific community with the instrumentation suited to the study of the Universe at high radio frequencies. SUNPIT will be suitable for the data of these new forthcoming receivers, when available for the scientific community.

SUNPIT produces a complete analysis of a solar map in about one hour, saving a directory which contains images, plots and several tables with the physical information of the solar disk and ARs (brightness temperatures, fluxes and spectral indices, with the respective errors). This pipeline – successfully tested – represents a crucial tool (1) to analyse solar images observed with the radio telescopes of the INAF Network, and (2) for the Space Weather monitoring network and forecast (soon available) along the solar cycle.

This INAF Technical Report was created with LaTeX.

Contents

1 Introduction: SUNdish PIpeline Tool (SUNPIT)

SUNPIT (SUNdish PIpeline Tool), described in this technical note, is designed for the imaging procedure and the data analysis of solar data acquired with some radio telescopes of the INAF Network (SRT and Medicina) in the context of the "SunDish Project" (PI: A. Pellizzoni)[1]. This project is active since 2018 for the imaging and monitoring of the solar atmosphere at high radio frequencies (at present 18 – 26.5 GHz) through single-dish observations. The SunDish project necessitated the development of several software packages – successfully tested – for the solar imaging (Single-Dish Imager, SDI, and SRT Single-Dish Tools, SDT) and the data analysis of the Active Regions (SUNDish Active Region Analyser, SUNDARA), therefore it was required to create this technical note to guide the user to properly reduce and analyse the solar radio data, both in mono-feed and in multi-feed approaches. This pipeline will also be suitable – with the appropriate arrangements – for the solar images obtained with the new receivers in Q-band (33 – 50 GHz) and W-band (70 – 116 GHz, [15]), soon installed at SRT in the context of the National Operative Programme (Programma Operativo Nazionale-PON)[2] [5]; this project will provide in the near future an upgrading with the new receivers up to 116 GHz also for the Medicina and Noto Radio Telescopes[3] [1]. The solar physics concerning the radio Sun and its emission mechanism are beyond the scope of this technical note; these details will be available in the upcoming paper about the SunDish project [17].

This technical note is organised as follows. Preliminary information about SUNPIT is reported in Section 2; download and installation procedure of SUNPIT are described in Section 3. The description of the imaging procedure for solar observations with INAF radio telescopes is reported in Section 4, and the data analysis with SUNDARA is described in Section 5. Finally, conclusions and future development of SUNPIT are reported in Section 6.

2 Preliminary information

SUNPIT is composed of three independent packages:

1. SDI **(Single-Dish Imager)**, based on the programming language IDL (Interactive Data Language[4]), a commercial software with specific INAF licence[5]. This IDL Package is designed to perform continuum and spectro-polarimetric imaging, optimized for On-the-fly (OTF) scan mapping, and suitable for most receivers/backends available at the INAF radio telescopes (see e.g. [2, 10, 18]); SDI receives in input the raw acquisitions (the original subscans) obtained by these radio telescopes, and produces output in the form of calibrated solar maps (Fig. 1). Details about the download and installation of SDI are available in Sect. 3.1, and the description of the imaging procedure with SDI is available in Sect. 4.1.

2. SDT **(SRT Single-Dish Tools)**, a Python Package[6] designed for the quicklook and analysis of single-dish radio data, starting from the backends present at every Italian

[1] https://sites.google.com/inaf.it/sundish

[2] https://sites.google.com/a/inaf.it/pon-srt/home

[3] https://indico.ict.inaf.it/event/1515/contributions/9080/attachments/4392/9080/PON_SRT_AUDIZIONE_31MAY21.pdf

[4] https://www.l3harrisgeospatial.com/Software-Technology/IDL

[5] Further details to obtain the Software licence are available at the ICT/INAF link https://www.ict.inaf.it/index.php/ict-inaf/software.

[6] https://www.python.org/

radio telescope. Substantially, this package is the Python counterpart of SDI imaging tool; the download/installation procedure of SDT is described in Sect. 3.2, and the imaging procedure is explained in Sect. 4.2.

3. SUNDARA **(SUNDish Active Region Analyser)**, a Python Package aimed at the automatic data analysis of solar images processed by SDI and/or SDT; SUNDARA receives in input the solar images obtained by SDI and/or SDT. This package produces in output a complete analysis in a short time (about 5 minutes for each solar map), saving a directory containing images, plots and several tables with physical information (brightness temperatures, fluxes and spectral indices, with the respective errors) of the Active Regions (ARs) detected in all the solar maps (Fig. 1). The download and installation procedures of SUNDARA are described in detail in Sect. 3.3, and the description of the data analysis is available in Sect. 5.

These packages are compatible with the following characteristics:

- at least Ubuntu 16.04 (64-bit PC desktop image), or macOS High Sierra 10.13.6; GNU/Linux environment can be installed also in the Windows Subsystem for Linux (WSL) directly on Windows, without the overhead of a traditional virtual machine or dualboot setup[7];
- at least 4 GB RAM (16 GB recommended);
- at least 10 GB of free disk space (necessary for both the installation and the data output);
- IDL 8.x.x or higher (for SDI);
- Python 3.7.X or higher (for SDT and SUNDARA).

Finally, the user is also free to download the preferred package of SUNPIT – among SDI, SDT, and SUNDARA – on the basis of the type of analysis which the user wishes to perform. For example, in case of the solar imaging procedure, the user can download only SDI and/or SDT; on the other hand, if the user has the solar maps produced by SDI or SDT and just wants to implement an AR analysis, he/she can download only SUNDARA. A simplified scheme of the SUNPIT operating is shown in Fig. 1.

2.1 Installation of the Anaconda (or Miniconda) system installer

It is strongly recommended for the user to install Anaconda[8] (version 4 or higher) or Miniconda[9] (version 3 or higher) in order to manage the Python environment and its libraries. Anaconda is a free and open-source system installer that allows to easily perform Python data science (and not only); Miniconda is a small version of Anaconda. The great advantage of this toolkit is the possibility to work with several Python environments allowing – for each of them – to install, update, and manage packages and libraries without interference with other packages and/or libraries installed in the operating system. Very briefly, once Anaconda (or Miniconda) is installed, following this Installation Procedure (preferably the "regular installation mode"), the user must create and install the preferred Python environment by issuing the command `conda create --name pxx python=v.v`, where

[7] https://docs.microsoft.com/en-us/windows/wsl/
[8] https://www.anaconda.com/products/individual
[9] https://docs.conda.io/en/latest/miniconda.html

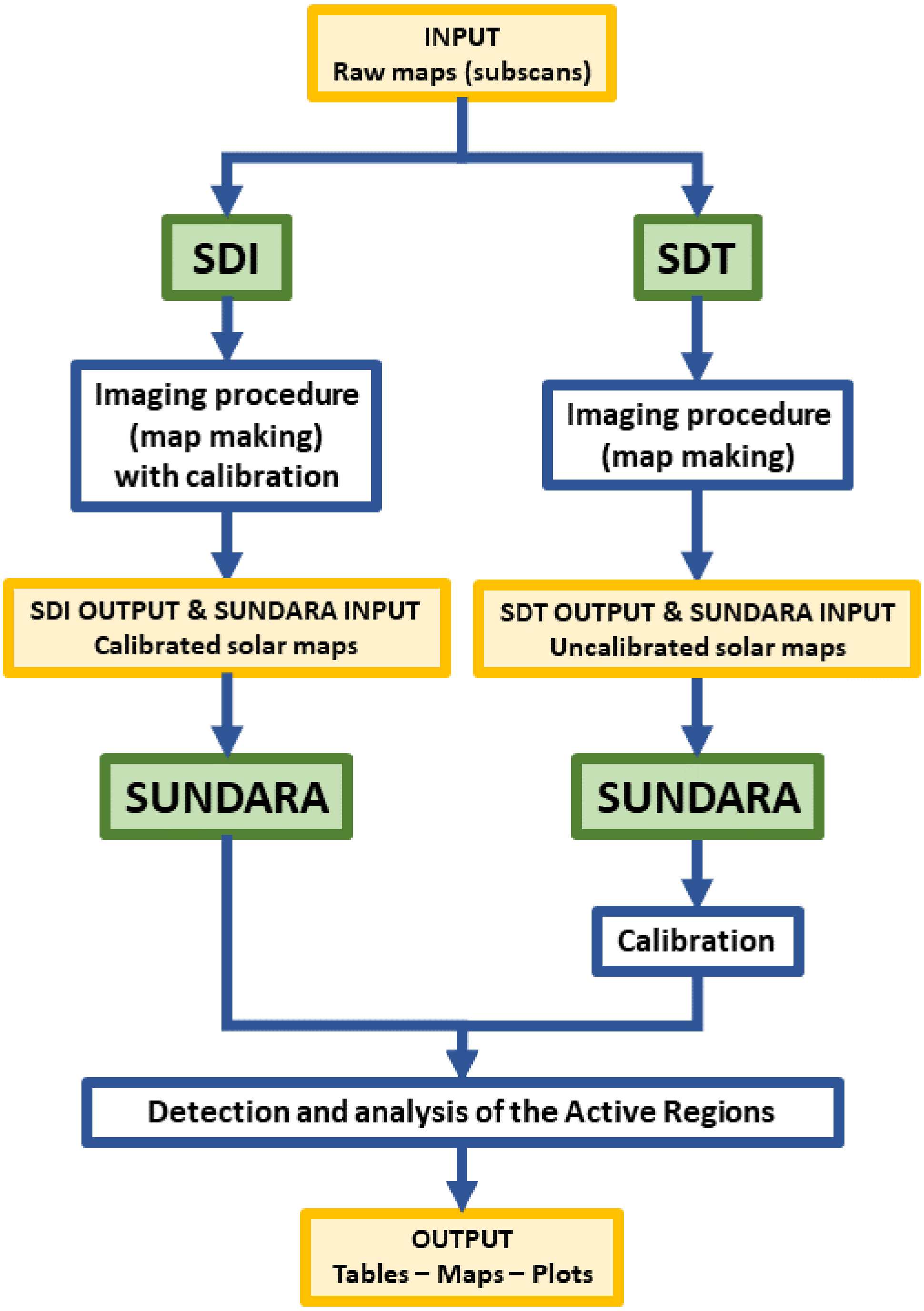

Figure 1: *Diagram of the* SUNPIT *operation. Input/Output are labelled by yellow boxes, and the software packages are indicated by green boxes.*

pxx is the name of the Python environment chosen by the user, and v.v is the selected version of Python[10]. Later, the user must access to the Python environment pxx through the command `conda activate pxx` (to deactivate the environment, please type the command `conda deactivate`), in order to use it. The user can download and manage packages and libraries through the conda management system[11].

2.2 The use of the feed receivers in SUNPIT

SUNPIT can be used to process and analyse the solar data obtained with SRT and the Medicina dish both in the "mono-feed mode" and in the "multi-feed mode".

In the first case, this pipeline considers only the reference feed of the receiver, usually the central one, for the analysis; in the second case SUNPIT uses the data recorded with all the feeds available for the receiver[12]. The multi-feed imaging procedure improves the exposure of the Sun as many times as the number of employed feeds.

To date the solar observations are available in K-band (18 – 26.5 GHz), in particular for the 7-feed receiver at SRT [16], and the dual-feed receiver at Medicina. The 7-feed receiver at SRT is composed by a central feed[13], surrounded by six lateral feeds arranged in hexagonal configuration (in the Gregorian focal plane); the central feed is labelled as 0, while the lateral feeds are labelled as 1 – 6. This translates into 14 sections/data streams in the FITS files, as each feed observes in two polarisations (left-hand circular polarisation, LCP, and right-hand circular polarisation, RCP). Using the dual-feed receiver at Medicina, the solar disk is typically observed through the single feed labelled as 1. Feed 0 is saturated for the solar disk signal level, in order to better observe the fainter coronal details. This is achieved by properly setting the attenuators, a procedure depending on the schedule file produced by the users, thus exceptions might exist in the many observing sessions carried out. Technical issues relative to the dual-feed receiver have caused some temporary changes in the recorded data structure; as of the publication date of this report, SUNPIT automatically considers them in the map-making process[14].

It is worth noting that the optimisation of the specific documentation – and the relative part of the software – about the handling of the feed positional information in the FITS files, used to align the data in the multi-feed imaging procedure, is currently underway.

3 Download and installation of SUNPIT

The download and installation procedures of SUNPIT are strictly connected with the independent solar packages (SDI, SDT, and SUNDARA), which are described in the following subsections. As opposed to SDT, released as open-source package, SDI and SUNDARA are available under the authorisation of the SunDish PI (Dr. A. Pellizzoni[15]);

[10] Recommended pxx= *p*39 and v.v= 3.9; for further details, please see the "Managing environments" and "Managing Python" sections at the following link: https://conda.io/projects/conda/en/latest/user-guide/getting-started.html.

[11] https://docs.conda.io/en/latest/

[12] This multi-feed tool in SUNDARA for SDT solar images is in test phase, and therefore we advise to use this procedure with caution.

[13] Please note that the 19-feed Q-band receiver will have a central feed, as opposed to the case of the 16-feed (4x4 pixels) W-band receiver.

[14] Starting from 6th July 2021, the feed 0 acquires only one polarisation due to a partial failure in this feed. Starting from 11th January 2022 this polarisation channel is designed to observe the solar disk.

[15] alberto.pellizzoni@inaf.it

regarding SUNDARA, also the authorisation of the developer (Dr. M. Marongiu[16]) is required.

3.1 SDI (Single-Dish Imager)

SDI package (v6.0_2022 is the last stable version[17]) can be downloaded from the section "Internal Documents and Data/SUNDISH Data Analysis SW" of the SunDish Google site. SDI does not need specific installation procedures, it is ready to be used once placed in the user's preferred folder.

3.2 SDT (SRT Single-Dish Tools)

The download and installation procedures of the Python Package SDT are described in detail at the official SDT link (`https://srt-single-dish-tools.readthedocs.io/en/latest/`).

3.3 SUNDARA (SUNDish Active Region Analyser)

The SUNDARA package (v1.2 is the last stable version) can be downloaded from the section "Internal Documents and Data/SUNDISH Data Analysis SW" of the SunDish Google site.

Before using SUNDARA, the user has to follow a few simple steps:

- download the folder `SD_sundara_v12` and place it in your preferred directory path;
- in the directory `SD_sundara_v12`, install the required Python libraries for the correct execution of SUNDARA by issuing the command `python sundara_easysetup_lib.py`;
- in the directory `SD_sundara_v12` check the existence of the sub-directory **`fits`** which contains some calibrated solar maps (in FITS file format) to be used as input files to SUNDARA for practice. These maps, obtained during the observing sessions at SRT and Medicina, are the output of the imaging procedure with SDI and the filename have the suffix `FEED_W_TI_IMAGE_SELFCAL.fits`, where W indicates the feed number of the receiver (see Sect. 2.2), TI indicates the imaging type called Total Intensity, and IMAGE_SELFCAL indicates that the image is self-calibrated (for further details see Sect. 4.3). The user can download other solar maps (with the same suffix and taking care to the feed, Sects. 2.2 and 4) from the column IMAGES (DS9 FITS) of the SunDish Archive[18], but these maps must be stored in the sub-directory **`SD_sundara_v12/fits`**;
- check the presence in the directory `SD_sundara_v12` of an example of the SunDish Archive `SUNDISH_v13.xlsx` (in .xlsx Excel spreadsheet file format) already available for the user for practice with SUNDARA; this archive contains the information of the solar maps collected during the observing sessions at SRT and Medicina, and it is crucial for the check phase of the observing parameters of the solar maps with

[16] `marco.marongiu@inaf.it`

[17] This version is updated with the last available ephemeris, and hence SDI works for solar maps obtained with the observations up to 31th December 2022. The user, in case of imaging procedure of solar observations beyond 31th December 2022, must wait for the next versions for coming years, based on the updated ephemeris.

[18] The access to this Archive, available at `https://sites.google.com/inaf.it/sundish/sundish-images-archive/sundish-archive-summary`, is subject to the authorisation of the SunDish PI (Dr. A. Pellizzoni).

SUNDARA. The user can download an updated version of this archive from the SunDish Archive;

- open the configuration file `sundara_input.ini` in the sub-directory `sun_utility` (see the Appendix A) and check the correct directory path (usually already set up with default directories and files), of (1) the downloaded SunDish Archive in the Excel spreadsheet file format (key `scaricato_excell`), (2) the solar maps in FITS file format (key `directory_fits`), and (3) the SUNDARA output files (key `directory_output`); this step is crucial to the proper run of SUNDARA.

Now, open a terminal window in the directory `SD_sundara_v12` and choose between two alternative approaches: (1) type the command `python sundara_v12.py`, or (2) type `run sundara_v12.py` in the `ipython` environment. Since SUNDARA requires a number of Python libraries, the user must check their presence and, if necessary, install the missing ones. Once these libraries are installed, the user can type again `python sundara_v12.py` (or `run sundara_v12.py` in the `ipython` environment); in case of successful installation of these libraries, an intuitive widget appears (Fig. 4), and the user is able to start the analysis of the solar data.

For further details about SUNDARA, see the relative INAF Technical Report [12].

4 Imaging procedure for solar observations with INAF radio telescopes

SUNPIT can be used to process and analyse solar data acquired within the framework of the SunDish project. Once the user has downloaded and stored the raw solar data (the original subscans) in a directory, the imaging procedure can begin. Solar images from both Medicina and SRT can be obtained through the packages SDI and/or SDT (Fig. 1).

When inspecting solar data from the SRT multi-feed K-band, the user should take into account that the central feed is labelled as `FEED_0` in the SDI output filename (in FITS file format), and the lateral feeds are labelled as `FEED_n`, where n indicates the number of the relative receiver feed. The central feed in SDT is labelled as `IMGFEED0` in the output FITS image, and the lateral feeds are labelled as `IMGFEEDn`; the data are contained in the extensions `IMGFEEDn_LCP` and `IMGFEEDn_RCP` of the FITS file, one for each polarisation. Regarding the dual-feed K-band receiver of the Medicina radio telescope, since 6th July 2021 the user must consider as input file for the solar analysis with SUNDARA the images labelled as `FEED_0` in the SDI output filename (even though the solar disk is observed with the `FEED_1`, Sect. 2.2), due to a data inversion in the FITS file of the raw data.

The imaging procedure described below can be skipped in case the user already has the solar maps obtained through SDI and/or SDT: in this scenario, see Sect. 5 for the solar data analysis with SUNDARA.

4.1 Imaging of solar data with the SDI Package

Regarding SDI, the user must follow these steps for a correct imaging procedure:

1. Create the working directory in the user's computer, in which all the output files will be saved after the procedure. It is recommended to create sub-directories, one for each project/image/epoch.

2. From a terminal window, go to the SDI folder, and run IDL from the same directory[19].

3. Execute the command **sd_install** from the IDL terminal window to select the working directory[20] (the specific sub-directory); a widget appears to the user (Fig. 2), who must (1) search for – and select by clicking – the working sub-directory through the "Directories" box on middle left of the widget, and (2) select the working sub-directory through one click in the "Files" box on middle right of the widget. Once clicked the "OK" button to confirm and exit from the widget, a summary pipeline instruction is displayed on the IDL terminal window.

4. Modify the **inputpars_sun_xxx** file (where xxx corresponds to `med` and `srt` for the Medicina and SRT images, respectively), which contains all the parameters and the information to execute the imaging procedure (see the Appendix B). The user can set some parameters in the `inputpars` file, such as the prefix of the output filenames (*outname*), and the pixel size of the solar images (*res*). Usually in the K-band at Medicina and SRT `res` generally ranges between 0.5 and 0.8 arcmin; if after the imaging procedure black pixels appear in the image, please select a higher value of `res`. Please note that (1) if the variable `outname` is not changed before starting a new analysis, the previous results will be overwritten, and (2) the `inputpars` file must be saved in the SDI folder, otherwise the imaging procedure with SDI will give an error message, resulting in the interruption of the analysis. Only for SRT, following the example of the `inputpars` file reported in the Appendix B (**inputpars_sun_srt**), in case of mono-feed mode, the user must comment the line **;**`feedmask(*)=1` and decomment the line `feedmask(0)=1`; on the other hand, in case of multi-feed mode, currently available only for the SRT multi-feed K-band receiver (18 – 26.5 GHz, [10]), the user must decomment the line `feedmask(*)=1` and comment the line **;**`feedmask(0)=1`.

5. Execute the IDL command **sd_init, 'inputpars_sun_xxx'** (xxx = `med` for Medicina; xxx = `srt` for SRT); this command uploads the imaging parameters written in the the most recent saved `inputpars` file. Please note that the run of this IDL command is necessary every time the user wants to further modify the parameters in the `inputpars` file.

6. Execute the command **sd_sun_ql** from the IDL terminal window; the same widget described in the point 3 appears to the user (Fig. 2), who in this case must consider the directory path of the raw solar data[21] in the "Directories" box. Solar maps obtained through SDI are calibrated according to the self-calibration procedure [17], where the image histogram (counts[22] distribution among pixels) – well modelled by a Gaussian – is compared to the quiet-Sun (QS) level, through a specific brightness reference for radio domain from [8], in order to find a count-to-Kelvin conversion factor; the user sees on screen one histogram (Fig. 3) for each polarisation channel (RCP and LCP).

[19] An SDI analysis performed outside the correct folder will give an error message, resulting in the interruption of the analysis.

[20] In case of the same working directory for different solar maps, this command can be skipped. In any case, we strongly suggest to run this command.

[21] The user should select only one solar map at a time for this analysis, because at the same observing session the RA and DEC solar maps are obtained with a time difference of about two hours; this difference is compatible with the solar activity (e.g., the emergence of a solar flare).

[22] Counts are defined as arbitrary electronics measure of the backend, without physics sense. This value is directly proportional to the flux density (and hence the brightness temperature).

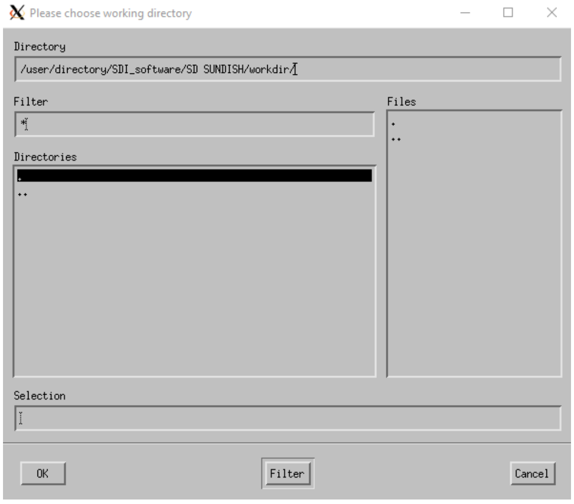

Figure 2: *Widget of* SDI *dedicated to both (1) the selection of the working sub-directory, and (2) the selection of the path of the raw solar data. The user must search for – and select by clicking – the desired directory through the "Directories" box on middle left of the widget, select the desired directory through one click in the "Files" box on middle right of the widget, and click the "OK" button to confirm and exit.*

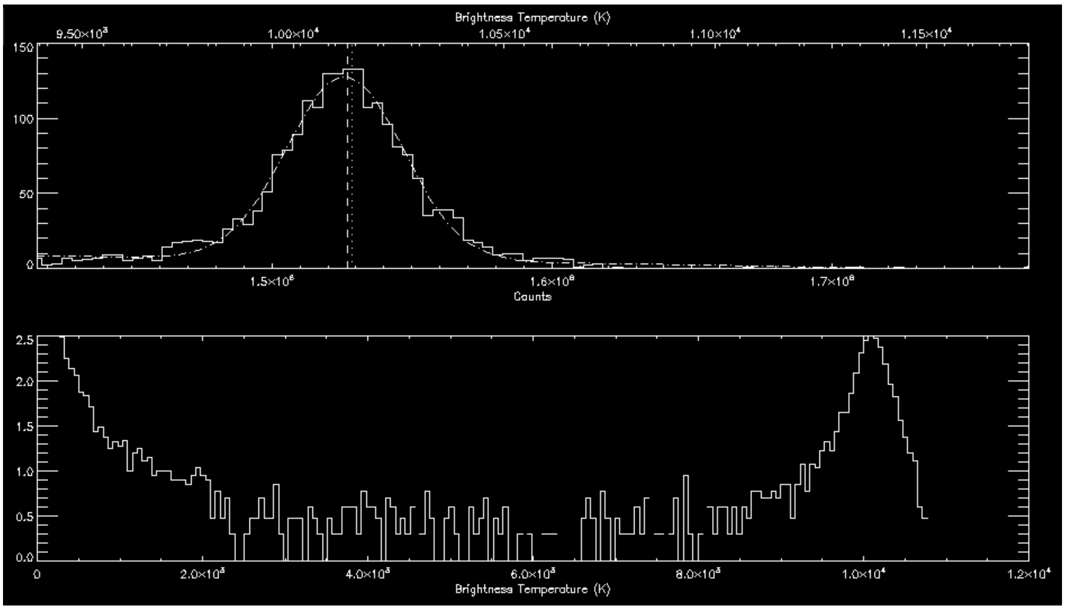

Figure 3: *Example of histogram of pixel values in the image, in linear scale, produced by the self-calibration process with* SDI. ***(top)*** *- Zoomed part of this distribution, well fitted by a Gaussian (dashed line), whose peak corresponds to the RMS value of the QS brightness temperature, and the width is connected with the solar activity.* ***(bottom)*** *- Complete histogram of the brightness temperature distribution. The tail of the quasi-Gaussian distribution at low brightness temperature in the histogram is due to the brightness gradient of the corona.*

Once this process is successfully completed, the solar maps are stored in the working subdirectory previously selected.

Regarding the multi-feed mode with SRT, SDI produces several maps, one for each receiver feed (for example, one for the central feed and six more for each lateral feed in the SRT multi-feed K-band receiver [16, 10]). The user must merge these maps through the IDL command **`sd_combine`**, following these steps:

1. Modify the **`inputpars_sun_srt`** file, where the user must comment the line `;feedmask(*)=1`, decomment the line `feedmask(0)=1`, and modify the `MERGING` section as appropriate (see the Appendix B).

2. Execute the IDL command **`sd_init, 'inputpars_sun_srt'`** to update the imaging parameters written in the `inputpars_sun_srt` file.

3. Execute the IDL command **`sd_combine`** to merge the solar maps corresponding to the feeds of the receiver.

The optimisation of the baseline subtraction and the relative flagging procedure with SDI is beyond the scope of the present technical note (for further details, see [2, 10, 9]).

4.2 Imaging of solar data with the SDT Package

For the imaging procedure with SDT, the user must follow these steps:

- open a terminal window in the directory where the data are located;

- type the command **`SDTinspect */ -d`** to automatically organise the observations in groups; these output files, called configuration files (in .ini file format, see the Appendix C). If this command produces many configuration files, the user can manually modify the file associated with the Sun.

- open the .ini configuration file of the Sun (see the Appendix C) and modify the keys "`projection`" in `projection = TAN`, and "`pixel_size`" in `pixel_size = x`, where x is the pixel resolution of the image in units of arcmin (see Sect. 4.1, point 4).

- type the command **`SDTimage -c config_file.ini --quick --noplot --frame sun`** to produce the image whose the output filename ends with "_sun.fits". `--quick` and `--noplot` options allow to save time in the plotting procedure of the data. In addition, the `--destripe` option, used to remove scanning effects (for example, clouds moving in the atmosphere), works only in maps that are scanned at least once along two orthogonal directions (RA and DEC, see Footnote 21), as described in [14].

The final solar map obtained through SDT is uncalibrated; then, SUNDARA is able to implement an accurate image calibration. For further details about imaging procedure with SDT, see the SDT imaging tutorial. Currently the imaging procedure for Medicina with SDT is available only for the solar maps obtained through the `FEED_0` starting from 6th July 2021; the same procedure for Medicina is under development for the `FEED_1` (for further details, see Sect. 4), and therefore in this case we refer to SDI for the imaging procedure (see Sect. 4.1).

4.3 Output files in the imaging procedure

At the end of the imaging procedure, the output files are stored in the working directory (for SDI) and/or in the directory where the data are located (for SDT). In case of SDI, the user must consider the solar map whose filename ends with `FEED_W_TI_IMAGE_SELFCAL.fits`, where:

- W indicates the receiver feed, in particular $W = 0$ for SRT, $W = 1$ (or $W = 0$, see Sects. 2.2 and 4) for Medicina, and $W = M$ for multi-feed mode;
- TI indicates the imaging type called Total Intensity, consisting in the average between the two polarisation channels (RCP and LCP) of the receiver;
- IMAGE_SELFCAL indicates that the image is self-calibrated, and hence the solar map is represented in units of Kelvin (only for the SDI filename); otherwise, the image is uncalibrated, resulting in a solar map represented in units of counts (for further details, see [17]).

In case of SDT, the user must take into account the FITS solar map which contains, as extensions, the individual maps for each polarisation and feed.

These output filenames produced by SDI and/or SDT must be renamed according to the following configuration:

- `SUN_TEL_YYMMDD_HHMM_XX.XGHz_Z.Zr_FEED_W_TI_IMAGE_SELFCAL.fits` ⇒ SDI;
- `SUN_TEL_YYMMDD_HHMM_XX.XGHz_Z.Zr_SDT.fits` ⇒ SDT;

where:

- SUN indicates the source (the Sun);
- TEL indicates the radio telescope (SRT for Sardinia Radio Telescope, MED for Medicina, and NOT for Noto), visible from the keyword `ANTENNA` in the primary header of the FITS file of the raw data;
- YYMMDD indicates the observation epoch (year/month/day), visible from the directory name of the raw data;
- HHMM indicates the starting time of observation (hours/minutes), visible from the directory name of the raw data;
- XX.X indicates the central observing frequency (in units of GHz)[23];
- Z.Z indicates the pixel size (in units of arcmin);
- SDT indicates that SDT Python Package has been used in the imaging procedure; otherwise, this part is undeclared.

These FITS files, organised with a correct filename, are crucial to execute the data analysis with SUNDARA.

[23] In SDI, the central observing frequency is visible by issuing the command **`sd_importfits`** from the IDL terminal window. In SDT, this frequency is calculated as $\nu_0 + 0.5 \times \delta\nu$, where ν_0 is the starting frequency (in units of GHz) and $\delta\nu$ is the bandwidth (in units of GHz); ν_0 and $\delta\nu$ are visible in the header of the FITS file of the SDT final solar image through the keys `frequency` and `bandwidth`, respectively.

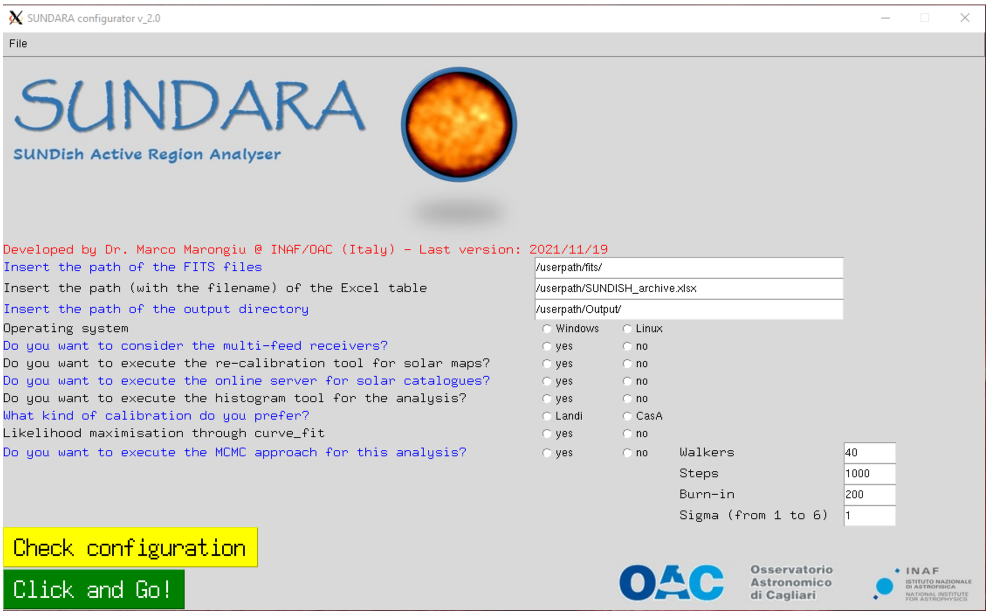

Figure 4: *Widget of the* SUNDARA *Python Package. The user must compile all the boxes before clicking the "Click and Go!" button, and hence executing* SUNDARA.

5 Data analysis: usage of SUNDARA

The imaging procedure – performed by SDI and/or SDT – creates a group of solar maps in FITS file format and organised with a correct filename (Sect. 4.3 and Fig. 1). These maps are collected in a specific directory, whose path is reported in the variable `directory_fits` of the file `sundara_input.ini` (see Sect. 3.3 and Appendix A); this file contains all the FITS filenames (according to the procedure described in Sect. 4.3) in the array `name_fits_array`[24], in order to be processed by SUNDARA.

SUNDARA has been successfully tested on about 200 solar maps from observations with SRT and Medicina. This Python Package receives in input these solar maps, and produces in output a complete analysis in a short time (about 5 minutes for each solar map), saving a directory containing images, plots and several tables with physical information (brightness temperatures, fluxes and spectral indices, with respective errors) of the ARs detected in all the solar maps (Fig. 1). SUNDARA unearths candidate ARs through several algorithms, that search patterns consistent with an elliptical 2D-Gaussian kernel [12]. The detected ARs are further modelled through an elliptical 2D-Gaussian function with noise [11].

The intuitive widget of SUNDARA appears (Fig. 4) by issuing the command `python sundara_v12.py` (or `run sundara_v12.py` from the `ipython` environment). After filling the form with the required details for the analysis, the "Check configuration" yellow button allows to verify the configuration from a terminal window, and eventually to modify this configuration. Once satisfied with the selected configuration, the "Click and Go!" green button allows to execute SUNDARA.

This widget requires to specify the following parameters:

- **"Insert the path of the FITS files"**, **"Insert the path (with the filename) of the Excel table"**, **"Insert the path of the output directory"** ⇒ In these

[24] Currently, the `name_fits_array` is updated to December 2020; further solar maps can added from the user.

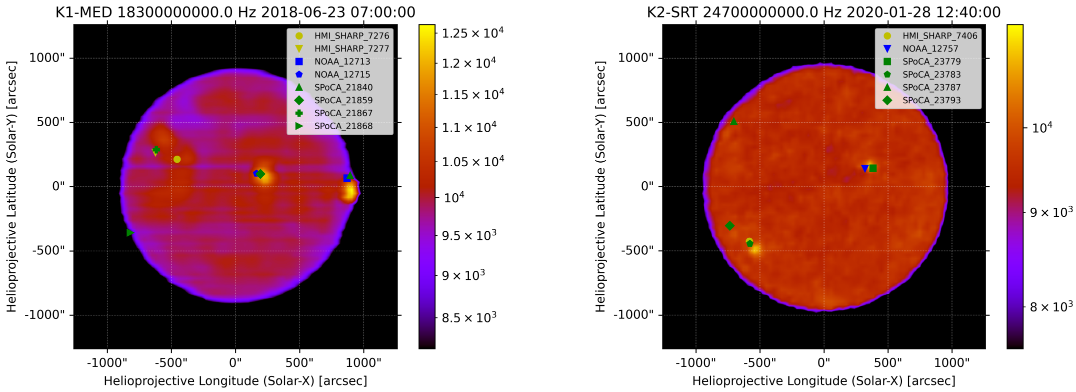

Figure 5: *Image of the Sun at* ***(left)*** *18.3 GHz obtained with Medicina on June 23th 2018, and* ***(right)*** *at 24.7 GHz obtained with SRT on January 28th 2020. In these solar maps are marked by symbols and the relative legend (at the top right) the detected ARs (if present) at the same observing epoch of the INAF observations, reported at other observing frequencies in the Heliophysics Event Knowledgebase (HEK).*

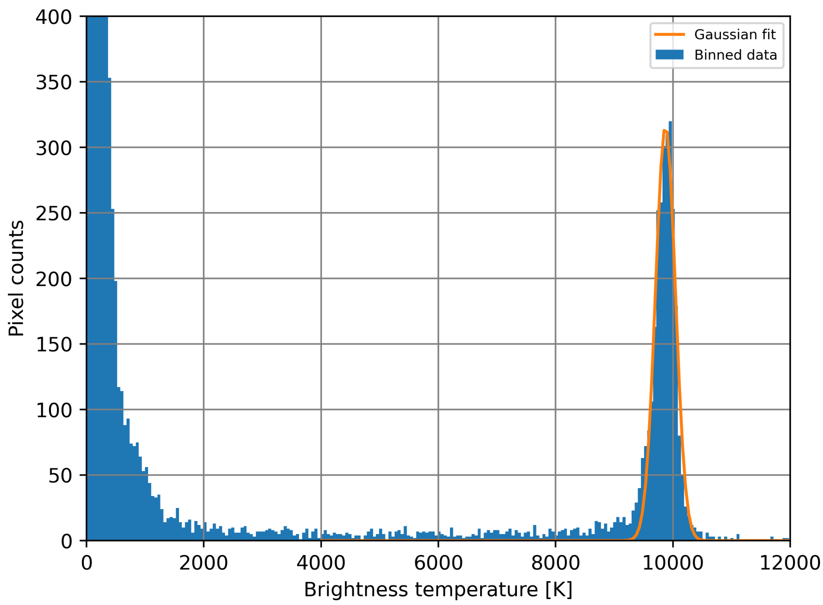

Figure 6: *Histogram of the pixel values in the solar images after the self-calibration process. The histogram is referred to the 18.3 GHz observation performed on June 23th 2018 at Medicina. The upper part of the distribution is well fitted by a Gaussian (orange line), whose peak corresponds to the RMS value of the QS brightness temperature, and the width is connected with the solar activity. The low-counts tail of the quasi-Gaussian distribution in this histogram is due to the brightness gradient of the corona.*

boxes there are already the default directory paths – inserted by the user during the installation of SUNDARA (Sect. 3.3) – of (1) the working directory of the FITS files, (2) the Excel table of the SunDish archive (Sect. 3.3), and (3) the output directory. These directory paths can be changed by the user, modifying these widget boxes.

- **"Operating system"** ⇒ The user can select the operating system between Linux and Windows.

- **"Do you want to consider the multi-feed receivers?"** ⇒ For the SRT solar images obtained with SDT, the user can select if consider only the central feed (mono-feed mode) or all the feeds of the receiver (multi-feed mode), with the automatic production of the merged solar image.

- **"Do you want to execute the re-calibration tool for solar maps?"** ⇒ Only for the calibrated solar maps obtained with SDI, the user can execute a new self-calibration procedure, if necessary; in case of uncalibrated solar maps obtained with SDT, these maps are automatically self-calibrated with the re-calibration tool of SUNDARA.

- **"Do you want to execute the online server for solar catalogues?"** ⇒ The user can select a specific tool that automatically associates the AR candidates in position with the detected ARs at other observing frequencies (Fig. 5), reported in the Heliophysics Event Knowledgebase (HEK [7])[25].

- **"Do you want to execute the histogram tool for the analysis?"** ⇒ The user can select the analysis of the histogram of the brightness temperature distribution (Fig. 6), to calculate the width σ of the Gaussian distribution (with its uncertainty), indicative of the solar activity.

- **"What kind of calibration do you prefer?"** ⇒ The user can select the type of calibration. "Landi" indicates the self-calibration procedure, as implemented by SDI [8, 17]; "CasA" indicates a specific absolute brightness calibration procedure with respect to the young and bright Cas A (3C461) Supernova Remnant, an ideal flux calibrator circumpolar at the INAF radio telescopes latitudes, and characterised by a high flux density (about 2,400 Jy at 1 GHz) [17].

- **"Likelihood maximisation through curve_fit"** ⇒ The user can select the `curve_fit` tool (`yes` button) of the SciPy Python library [20], that uses the non-linear least squares procedure to model the ARs detected in the solar disk through SUNDARA. Otherwise (`no` button), ARs are modelled through the maximum log-likelihood method.

- **"Do you want to execute the MCMC approach for this analysis?"** ⇒ The user can select a deep analysis (also a few hours) through EMCEE Python Package[26] [4], based on the Markov Chain Monte Carlo (MCMC) analysis in the Bayesian approach. EMCEE is able to flush out degeneracies in the model parameters, with the aid of corner plots [3][27]. These parameters are constrained through the definition of prior distributions that encode preliminary and general information; SUNDARA considers uniform priors, but the exact ranges are still under development. In the MCMC

[25] https://www.lmsal.com/hek/index.html

[26] https://emcee.readthedocs.io/en/stable/

[27] A corner plot is an illustrative representation of different projections of samples in high-dimensional spaces to reveal covariances.

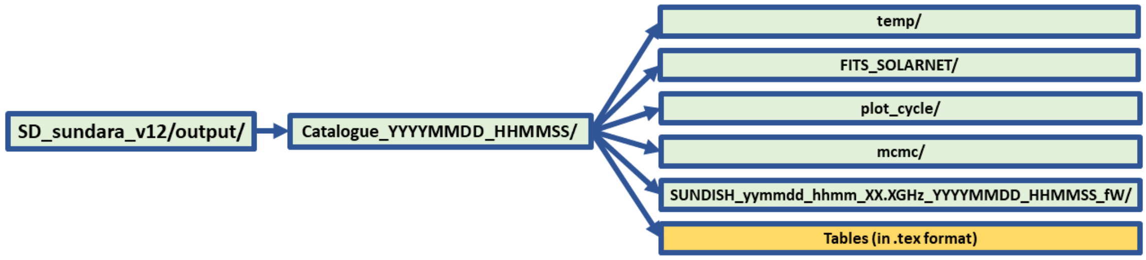

Figure 7: *Structure of the* SUNDARA *output. YYYYMMDD and HHMMSS indicate the epoch (year/month/day) and the time (hours/minutes) of saving file in the user's computer, respectively; yymmdd and hhmm indicate the epoch (year/month/day) and the starting time of observation (hours/minutes) of the solar map, respectively; XX.X indicates the central observing frequency (in units of GHz) of the solar map; W indicates the receiver feed, in particular $W = 0$ for SRT, $W = 1$ (or $W = 0$, see Sects. 2.2 and 4) for Medicina, and $W = M$ for the multi-feed mode. Green boxes indicate directories, and the orange box indicates the presence of tables in .tex format (useful for Latex tables).*

analysis, the beginning of the ensemble sampler is characterised by an initial period – called "burn-in", discarded by the analysis – where the convergence of the average likelihood across the chains is unstable (default chains: 200; recommended: 500). The number of subsequent Markov chains (steps) is set up between 10^3 (default) and 10^4 (recommended), depending on the computational characteristics, with a recommended number of 40 walkers. All the uncertainties are reported at 68% (1σ, recommended).

For further technical details about SUNDARA, see [12].

5.1 Output of SUNDARA

As shown in Fig. 7, the path `SD_sundara_v12/output` contains all the output files produced by SUNDARA. In particular, the output of each execution of SUNDARA is stored in the sub-directory `Catalogue_YYYYMMDD_HHMMSS`, containing images, plots and several tables with physical information of the ARs detected in the solar maps; this sub-directory contains the following folders:

- `temp` ⇒ tables for each analysed solar map;
- `FITS_SOLARNET` ⇒ all the analysed solar maps in FITS file format, with the header compatible with the SOLARNET metadata recommendations for solar observations [6];
- `plot_cycle` ⇒ all the plots about the time evolution of the solar flux density for each observing frequency and radio telescope;
- `mcmc` ⇒ tables, plots, and corner plots from the MCMC analysis in the Bayesian approach (this directory appears only when the user activates the mcmc option);
- `SUNDISH_yymmdd_hhmm_XX.XGHz_YYYYMMDD_HHMMSS_fW` ⇒ images, plots and tables with the physical information of the ARs detected in the solar maps; SUNDARA saves one directory for each solar map.

Moreover, the directory name `SUNDISH_yymmdd_hhmm_XX.XGHz_YYYYMMDD_HHMMSS_fW` could include the following suffixes (zero or more), indicating warning messages for the user:

- FREQ ⇒ the central frequency reported in the FITS filename of the solar map does not correspond to the central frequency reported in the Excel table of the SunDish archive (Sect. 3.3);
- TM ⇒ the minute value of the starting time reported in the FITS filename of the solar map does not correspond to the minute value of the starting time reported in the Excel table of the SunDish archive;
- TH ⇒ the hour value of the starting time reported in the FITS filename of the solar map does not correspond to the hour value of the starting time reported in the Excel table of the SunDish archive;
- TA ⇒ all the starting time reported in the FITS filename of the solar map does not correspond to all the starting time reported in the Excel table of the SunDish archive;
- OUT ⇒ the observing epoch of the analysed solar map is not included in the Excel table of the SunDish archive;
- D ⇒ the calibration tool identifies a double Gaussian in the histogram of the brightness temperature (see [12] and [17] for further details).

The folder Catalogue_YYYYMMDD_HHMMSS contains also 11 tables (in .tex file format); the user, for their analysis, can consider these 4 tables[28], that include – in a compact manner – the physical information of the ARs detected in the solar maps:

- **07_table_flusso_tutto_finale.tex** ⇒ the flux densities for each AR detected in the solar maps;
- **08_table_spindex_tutto_finale.tex** ⇒ the spectral indices calculated for each AR detected in a specific observing epoch (and for each radio telescope);
- **09_table_idcard_finale.tex** ⇒ the general information about the solar maps analysed with SUNDARA (for example, the total flux density of the solar disk, and the number of detected AR for each solar map);
- **10_table_idcard_corr.tex** ⇒ similar to the previous table, but the total flux density of the solar disk is normalised with respect to the perihelion.

In these tables the following information are reported:

- ***ID*** ⇒ the identification number for every single map in the format XB, where X indicates the radio telescope (M for Medicina, S for SRT, and N for Noto), and B indicates the ID number of the map.
- ***Epoch*** ⇒ the observation date (expressed as yy-mm-dd).
- ***T*** ⇒ the acquisition time interval of the map (in units of Universal Time).
- ν_{obs} ⇒ the central observing frequency (in units of GHz).
- σ_{disk} ⇒ the standard deviation of the solar disk brightness distribution with respect to the QS-level (in units of K).

[28]The tables with a prefix between 00 and 06 essentially contain the same information of the tables with prefix between 07 and 10, with more significant digits.

- $AR_n \Rightarrow$ the number of identified ARs in each solar map.
- $F \Rightarrow$ the total flux density (in units of sfu[29]) of the solar disk (with uncertainty), normalised with respect to the perihelion.
- $ar\_id \Rightarrow$ the AR name (if present), according to the HEK archive.
- ***Size*** $\Rightarrow$ the AR size, at twice the fitted semi-axes level (in units of arcmin^2).
- $T_{p,tot}$ and $T_{p,ex} \Rightarrow$ the maximum brightness temperature and the peak of the excess brightness temperature, respectively, for each AR (with uncertainties). The excess brightness temperature of ARs above the QS level, T_{ex}, is defined as $T_{p,tot} - T_{b(QS)}$, where $T_{b(QS)}$ is the QS temperature.
- S_{sub} and $S_{tot} \Rightarrow$ the AR flux density of the QS-subtracted image and the original image, respectively (in units of sfu); these values are given by the Rayleigh-Jeans approximation, with uncertainties [12].
- α_{T_p}, $\alpha_{T_{ex}}$, and $\alpha_{tot} \Rightarrow$ the spectral indices (with uncertainties) referred to $T_{p,tot}$, T_{ex}, and S_{tot}, respectively [19, 12];
- ***Notes*** $\Rightarrow$ further AR flags ("b" indicates if the AR position is located outside of the 95%-level of the solar radius; "k" indicates the distance between 2 different ARs $\leq$ 2 beams of the receiver; "C" indicates an AR located inside a confused region; sequential numbers are related to multiple AR detection for the same observing session).

Finally, the user analyses the contents of the output directory and evaluates, through visual inspection, the possibility to reject a part of the final automatic analysis, in order to avoid fake AR detection.

6 Conclusions and future development of SUNPIT

This technical note illustrates SUNPIT, the pipeline aimed at the imaging procedure and the data analysis of the radio solar data – and guides the user to properly reduce and analyse the solar data. SUNPIT is designed for the radio data acquired with some INAF radio telescopes (SRT and Medicina). The present technical note follows the development of software for solar imaging and data analysis, performed in the framework of the "SunDish Project" (PI: A. Pellizzoni).

SUNPIT produces a complete analysis of a solar map in about one hour, saving a directory which contains images, plots and several tables with the physical information of the solar disk and ARs (brightness temperatures, fluxes and spectral indices, with respective errors). This pipeline – successfully tested – represents a crucial tool (1) to analyse the solar images observed with the radio telescopes of the INAF Network, and (2) for the Space Weather monitoring network and forecast (soon available) along the solar cycle.

Code optimisation and improvement as well as more extensive tests with other solar datasets will make SUNPIT an even more complete tool for the solar physics thanks to future implementation of other physical aspects in SUNDARA (for example, polar brightening and coronal holes), and further input FITS files coming from other international facilities

[29]The solar flux unit (sfu) is a convenient measure of flux density often used in solar radio observations; 1 sfu corresponds to 10^4 Jy.

in a broad range of the electromagnetic spectrum (from radio to X-ray frequencies). Last but not least, this pipeline will also be suitable for the solar images obtained with the new receivers up to 116 GHz, soon installed at SRT (and in the near future also at Medicina and Noto) in the context of the PON project.

These improvements are crucial for a future complete sharing of SUNPIT with the international community; for further information and collaboration, the reader is encouraged to contact the authors of this technical note.

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Carey, İlhan Polat, Yu Feng, Eric W. Moore, Jake VanderPlas, Denis Laxalde, Josef Perktold, Robert Cimrman, Ian Henriksen, E. A. Quintero, Charles R. Harris, Anne M. Archibald, Antônio H. Ribeiro, Fabian Pedregosa, Paul van Mulbregt, and SciPy 1.0 Contributors. SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. Nature Methods, 17:261–272, 2020.

A The configuration file in the SUNDARA Python Package

The Python Package SUNDARA contains the configuration file `sundara_input.ini` in the sub-directory `sun_utility`. This file is composed by four sections, that we briefly present below with the respective tasks:

- FUNDAMENTALS ⇒ name of the parameters for the MCMC analysis (see Sect. 5);
- DIRECTORIES ⇒ path of the Sundish Archive (in Excel spreadsheet format)[30], the directories of the solar FITS images, and SUNDARA output files;
- CONSTANTS ⇒ several constants and parameters for the solar analysis with SUNDARA;
- FITS FILES ⇒ the list of the solar FITS images to analyse; please comment the FITS files temporarily unnecessary for the analysis.

```
[fundamentals]
name = SUNDISH
names_mcmc = amp posx posy ax bx angle noise


[directories]
scaricato_excell = ./SUNDISH_v13.xlsx
directory_fits = ./fits/
directory_output = ./output/


[constants]
angolo = 0.                 # rotation angle of the 2D-Gaussian
epsilon = 1e-12
number_near = 3             # alert for beams (close active regions)
number_near_hv = 2.5        # alert for beams (helioviewer)
num_soglia = 10.
num_rms = 3.                # RMS threshold for active region detection
n_sigma = 2.                # sigma threshold for active region detection
nthr = 2.7                  # thresold value for automatic detection in photutils


[FITS files]
name_fits_array =
                  SUN_MED_180215_1120_24.1GHz_0.6r_FEED_1_TI_IMAGE_SELFCAL.fits
                  #SUN_MED_180215_1222_24.1GHz_0.6r_FEED_1_TI_IMAGE_SELFCAL.fits
                  #SUN_MED_180219_1014_24.1GHz_0.5r_FEED_1_TI_IMAGE_SELFCAL.fits
                  [...]
                  SUN_SRT_190517_0840_25.5GHz_0.5r_FEED_0_TI_IMAGE_SELFCAL.fits
                  #SUN_SRT_190517_1025_25.5GHz_0.8r_FEED_0_TI_IMAGE_SELFCAL.fits
                  #SUN_SRT_191009_1146_18.8GHz_0.6r_FEED_0_TI_IMAGE_SELFCAL.fits
                  [...]
```

[30] This part is already set up with the default file `SUNDISH_v13.xlsx`.

B The `inputpars` file in SDI

SDI includes two `inputpars` files (**`inputpars_sun_med`** for the Medicina Radio Telescope, and **`inputpars_sun_srt`** for SRT) that contain all the parameters and the information to execute the imaging procedure. Here we report only one file, where the red parts are belonging to Medicina, and the green parts are belonging to SRT. For reasons of clarity, each option in the `inputpars` file is explained with a comment.

This file is composed by several sections, that we briefly present below with the respective tasks:

- IMPORTFITS ⇒ loading and opening of the FITS file and the backend selection;
- CORCONVERT ⇒ computation and application of the feed coordinates (the coordinate type is chosen in the section SUNCONVERT);
- BASESUB ⇒ the baseline subtraction [2, 10, 9, 17];
- MERGING ⇒ merging of the feeds (only for multi-feed mode);
- AUTOFLAG ⇒ RFI detection and subtraction [17];
- IMAGING ⇒ setup of the map resolution, coordinate type, and the type of data;
- CALIBRATION ⇒ setup of gain of the receiver and the sky opacity `tau0` at zenith. In particular, `tau0` is usually obtained from the Skydip observing mode, that measures the sky brightness at a range of elevations; a more accurate value of `tau0` is obtained with a radiometer (to date present only at SRT).
- SUN_SELFCAL ⇒ calibration parameters for the self-calibration of the solar maps [17, 13].

```
; INPUT TEMPLATE:

print
print,'%%%%%%%%%%%%%%%%%%'
print,'LOADING INPUTPARS_SUN_XXX'   ; for the Sardinia Radio Telescope XXX=SRT
                                    ; for the Medicina Radio Telescope XXX=MED
print,'%%%%%%%%%%%%%%%%%%'
print

allow_interactive=1


; IMPORTFITS

restore,'workingdir.temp'

outname='SUN_XXX'

bck_mode='SK77S'                    ; SRT K-band MF full-stokes
bck_mode='TP_MED_K'                 ; Med K-band MF total-intensity
```

```
feedmask=intarr(7)
feedmask(0)=1                       ; SRT central feed only
;feedmask(*)=1                      ; SRT multi-feed only
feedmask(0:1)=1                     ; Med dual-feed

nchan=1024

; *** filter
flagfil=0                           ; spectral filter on/off  (=1 =>on)
filter0=1.5                         ; RFI filter
filter=0.3                          ; spectral filter threshold
filter0_df_L=10                     ; polyfit degrees of freedom (step 1, LEFT)
filter_df_L=10                      ; polyfit degrees of freedom (step 2, LEFT)
filter0_df_R=10                     ; polyfit degrees of freedom (step 1, RIGHT)
filter_df_R=10                      ; polyfit degrees of freedom (step 2, RIGHT)

chmin=100                           ; min frequency channel
chmax=1000                          ; max frequency channel

flagtable=1+intarr(nchan)           ; fixed spectral flag table

slow=0                              ; spectral plotting flag (=1 verbose)
slowrate=100.


; CORCONVERT

corconvert_flag=1                   ; if = 1 then computes and applies feed coordinates


; SUNCONVERT

sunconvert_flag=2                   ; =0, no conversion
                                    ; =1, ecliptic conversion
                                    ; =2, "delta ecliptic" conversion


; BASESUB

method=2                            ; (method 2) linear fit based on scan limits
thr=10                              ; (method 2) scan fraction parameter


; MERGING

nmaps=7                             ; number of selected maps
mapnames=strarr(nmaps)              ; map names
```

```
mapnames(0)='FEED_0.fits'          ; central feed 0
mapnames(1)='FEED_1.fits'          ; lateral feed 1
mapnames(2)='FEED_2.fits'          ; lateral feed 2
mapnames(3)='FEED_3.fits'          ; lateral feed 3
mapnames(4)='FEED_4.fits'          ; lateral feed 4
mapnames(5)='FEED_5.fits'          ; lateral feed 5
mapnames(6)='FEED_6.fits'          ; lateral feed 6

totalmapname='NOMEFILE_'
outname=totalmapname


; AUTOFLAG

res_rfi=15.                        ; RFI search subregion
rfi_par1=3                         ; minimum sample number
rfi_par2=0.8                       ; % of samples to average
sigma=-4                           ; RFI detection sigma level (if le 0, no flagging)


; IMAGING

res=0.6                            ; map resolution in arcmin
field=2                            ; data field to image
                                   ; (=0, raw counts; =1, basesub; =2, calib)
projtype='EclARC'                  ; coordinate/projection type
ra0='auto'                         ; map projection center (auto=auto centering)
dec0='auto'


; CALIBRATION

gfile='gaintable.txt'              ; gain table filename
tau0=0.                            ; sky opacity at zenith


; SUN_SELFCAL

historange=0.7                     ; counts histogram range
historange=0.8                     ; counts histogram range
nbin=100                           ; histogram bins
```

C The configuration file in the SDT Python Package

The Python Package SDT, thanks to the command **SDTinspect */ -d**, automatically organises the solar observations in a configuration file (in .ini file format), reported below. This file is composed by three sections, that we briefly present below with the respective tasks:

- LOCAL ⇒ path of the working and data directories;
- ANALYSIS ⇒ several keys for the analysis, such as the projection type (`projection`), the directory list of the solar observations (`list_of_directories`), the pixel resolution of the image in units of arcmin (`pixel_size`), and finally the directory lists – not necessary for the solar imaging with SDT – of the calibrators (`calibrator_directories`) and the Skydip (`skydip_directories`);
- DEBUGGING ⇒ the file format of the debugging files.

```
[local]
workdir = .
datadir = .
productdir = None

[analysis]
projection = TAN
interpolation = spline
prefix = test_
list_of_directories =
        20220111-091020-sundish-Sun_18/
calibrator_directories =
skydip_directories =
noise_threshold = 5
smooth_window = 0.05
pixel_size = 0.6
goodchans =

[debugging]
debug_file_format = jpg
```