Rapporti Tecnici INAF
INAF Technical Reports

Number	81
Publication Year	2021
Acceptance in OA@INAF	2021-03-18T21:10:27Z
Title	A Python approach for solar data analysis: SUNDARA (SUNDish Active Region Analyser), preliminary development
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Handle	http://hdl.handle.net/20.500.12386/30719, http://dx.doi.org/10.20371/INAF/TechRep/81

A Python approach for solar data analysis: SUNDARA (SUNDish Active Region Analyser), preliminary development

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Abstract

This technical note describes the Python package SUNDARA (SUNDish Active Region Analyser), a sophisticated code – fully self-consistent – aimed at the data analysis of solar images. This analysis is crucial for the INAF Proposal "SunDish Project" (PI: A. Pellizzoni), active since 2018 and devoted to imaging and monitoring the solar atmosphere at high radio frequencies (at present 18 – 26 GHz) through single-dish observations with INAF radio telescopes (SRT and Medicina).

SUNDARA, characterised by a very user-friendly widget, allows to automatically unearth Active Regions (ARs) across the solar disk (or on its edge) through several algorithms; these ARs are modelled through an elliptical 2D-Gaussian kernel. In little more than 5 minutes, SUNDARA produces a complete analysis of a solar map, saving a directory containing images, plots and several tables with physical information of the solar disk and ARs (brightness temperatures, fluxes and spectral indices, with respective errors). A deeper analysis (that can be completed in a few hours) is possible thanks to a Bayesian approach based on Markov Chain MonteCarlo (MCMC) simulations. Moreover, these identified ARs are automatically associate in position with the detected ARs at other observing frequencies, reported in the Heliophysics Event Knowledgebase (HEK) used by the astrophysics and solar physics communities.

SUNDARA has been successfully tested on a large amount of data from solar maps implemented with the radio telescopes of the INAF Network (SRT and Medicina). For the purposes of this technical note, we report only two cases (one for Medicina, and one for SRT).

This Python package constitutes a crucial tool for the INAF Network to analyse solar images (the Space Weather monitoring network and forecast along the solar cycle will be soon available), and to provide a complete overview of the astrophysical phenomena.

This INAF Technical Report was created with LaTeX.

Contents

1 Introduction: data analysis of solar images at radio frequencies

This technical note describes the Python package SUNDARA (SUNDish Active Region Analyser)[1]. SUNDARA has been specifically developed for the data analysis of solar images acquired with the radio telescopes of the INAF Network (SRT and Medicina).

The radio Sun is dominated by the quiet Sun emission, which covers the entire surface of the solar disk as a mostly uniform background emission with some additional brighter spots. These bright areas are called active regions (ARs): they are characterised by strong or intense local magnetic fields, and provide energy for solar flares and coronal mass ejections (CMEs).

The INAF Proposal "SunDish Project" (PI: A. Pellizzoni)[2] – active since 2018 for the imaging and monitoring of the solar atmosphere at high radio frequencies (at present 18 – 26 GHz) through single-dish observations – required an automatic computational package to identify ARs and measure their fluxes and spectra. This radio data analysis is now possible thanks to SUNDARA – a fully self-consistent sophisticated code – adapted for our purposes from Marongiu et al. 2020 [8].

This Python package – successfully tested by Pellizzoni et al. (in prep.) [11] – represents a crucial tool to analyse solar images observed with the radio telescopes of the INAF Network (the Space Weather monitoring network and forecast along the solar cycle will be soon available), and to provide a complete overview of the astrophysical phenomena.

2 Preliminary information

SUNDARA is compatible with the following characteristics:

- Ubuntu 12.04 (x32 or x64-based operating system) or recent versions as operating system;
- 4 GB or more of RAM;
- 1 GB or more of free disk space;
- python 3.X.X;
- emcee 3.X.X;
- anaconda 4.X.X or more.

2.1 Usage of SUNDARA

The usage of SUNDARA is very simple, thanks to an intuitive widget (Fig. 1). After filling the form with the required details for the analysis, the "Check configuration" yellow button allows to verify the configuration on the terminal, and eventually to modify the configuration. Once satisfied with the selected configuration, the "Click and Go!" green button allows to execute SUNDARA.

[1] https://sites.google.com/inaf.it/sundish/scientific-summary-of-the-project/observations-and-data-analysis/scientific-analysis-of-the-solar-images

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

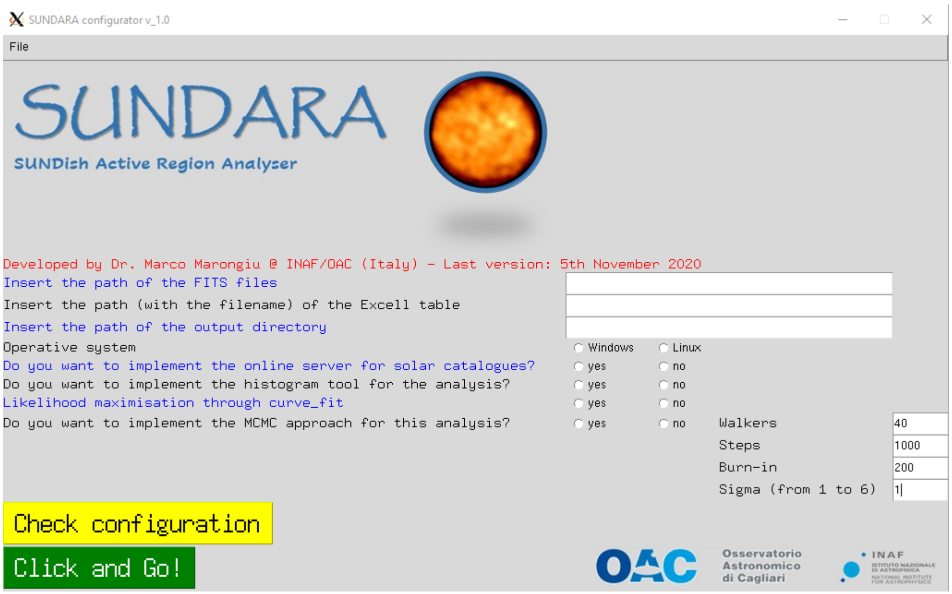

Figure 1: *Widget of* SUNDARA*. The user must compile all the boxes before clicking the "Click and Go!" button. In the Markov chain Monte Carlo (MCMC) analysis, the beginning of the ensemble sampler is characterised by an initial period –called "burn-in", discarded by the analysis– where the convergence of the average likelihood across the chains is unstable (default chains:* 200*; recommended:* 500*). The number of subsequent Markov chains (steps) are 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).*

The execution of SUNDARA is connected with the download in the user's computer from the Sundish Archive[3] of both the solar maps (in FITS file format) and the catalogue (the Sundish Archive in .xlsx Excel file format) of the information of these maps, collected during observing sessions at INAF sites of SRT and Medicina. The online image archive is structured to ease broadband data exploitation and it will be regularly updated a few hours after each new observation. The FITS files are stored in a specific work directory, whose path must be typed in the box "Insert the path of the FITS files" of the widget[4]; in the same way, the Excel table is located in a work directory, whose path must be reported in the box "Insert the path (with the filename) of the Excel table" of the widget (Fig. 1).

2.2 Composition of SUNDARA

SUNDARA consists in a sophisticated Python architecture (Fig. 2), composed of several environments:

sundara_input.py This file contains the array of the FITS filenames of the solar maps, necessary for the data analysis.

sundara_func.py In this file there are the functions necessary for the data analysis (such as flux densities and spectral indices).

sundara_plot.py This part contains the functions to plot the images.

[3]This catalogue is in the Excel spreadsheet format, available at https://sites.google.com/inaf.it/sundish/sundish-images-archive/sundish-archive-summary

[4]SUNDARA is able to automatically analyse both a single map and an array of maps.

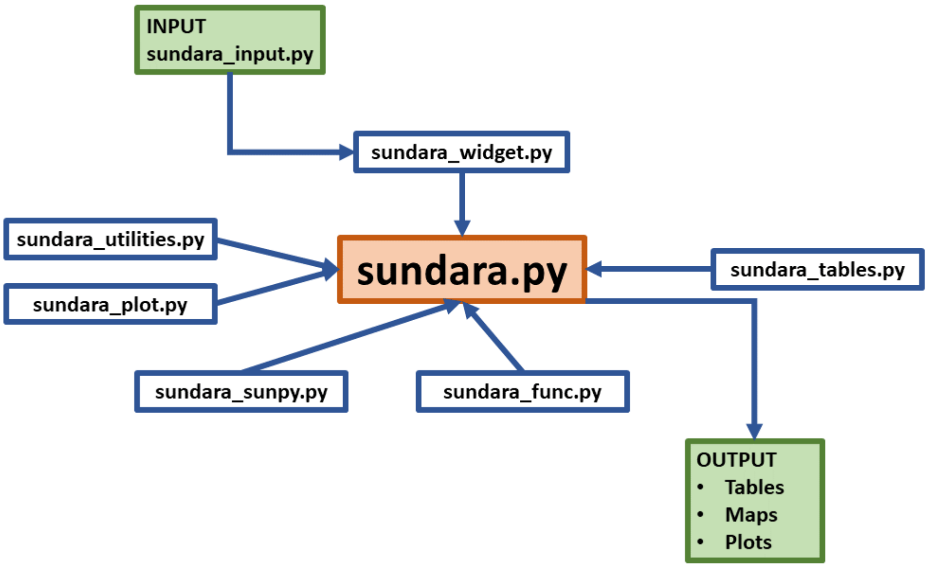

Figure 2: *Diagram of* SUNDARA. *Input/Output are labelled in green.*

sundara_tables.py In these parts there are the functions responsible for the creation of the tables of results (stored both in .dat and in .tex formats).

sundara_sunpy.py This file includes the functions involved with SUNPY Python package[10].

sundara_utilities.py In this file there is the part regarding technical aspect of SUNDARA package.

3 SUNDARA (SUNDish Active Region Analyser)

The identification of the ARs and the calculation of their fluxes and spectra is possible thanks to SUNDARA. The process is based on several Python packages, such as PHOTUTILS[5], usually adopted for detecting and performing photometry of astronomical sources [1], and SUNPY[6], an open-source package for solar data analysis [10]. SUNDARA receives in input solar maps (in standard FITS format) performed using the SRT Single-Dish Imager (SDI), which is a tool designed to perform continuum and spectro-polarimetric imaging, optimized for On-the-fly (OTF) scan mapping, and suitable for most receivers/backends available for INAF radio telescopes (see e.g. [2, 7, 12]).

As a first step, SUNDARA adjusts the FITS header of each map according to the solar maps features (Fig. 3) shared with the solar physics community [17]. After that, this Python package implements the histogram of the brightness temperature distribution (Fig. 4), to calculate the width σ of the Gaussian distribution (with its uncertainty), indicative of the solar activity.

For a better AR identification, SUNDARA subtracts the quiet-sun average brightness from the calibrated images, highlighting the flux anomalies and features on the solar disk (or in its edge/limb). This results in maps with only the excess brightness temperature above the quiet-sun level (Fig. 5). The procedure unearths candidate ARs through four different

[5] https://photutils.readthedocs.io/en/stable/
[6] https://sunpy.org/

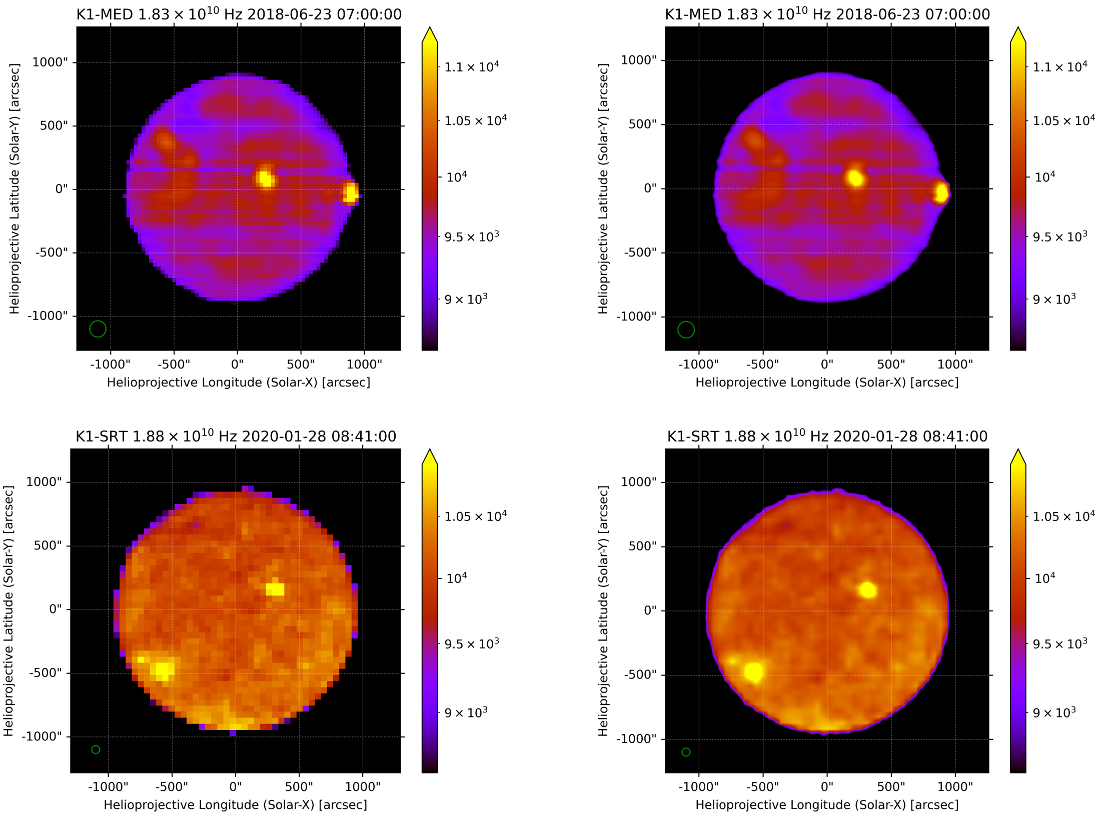

Figure 3: *(top left) Solar disk image at 18.3 GHz obtained with the Medicina Radio Telescope on June 23th 2018, processed with* SUNDARA *package; (top right) rebinned image (3000 × 3000 pixel) of the same solar disk image. (bottom left) Solar disk image at 18.8 GHz obtained with SRT on January 28th 2020, processed with* SUNDARA *package; (bottom right) rebinned image (3000 × 3000 pixel) of the same solar disk image. Colorbars indicate the brightness temperature of the solar maps in units of Kelvin. The green circles on the bottom left indicate the beam size at the observed frequencies; pixel sizes are 2.13 (at Medicina) and 1.04 arcmin (at SRT) for 18.3 and 18.8 GHz maps, respectively.*

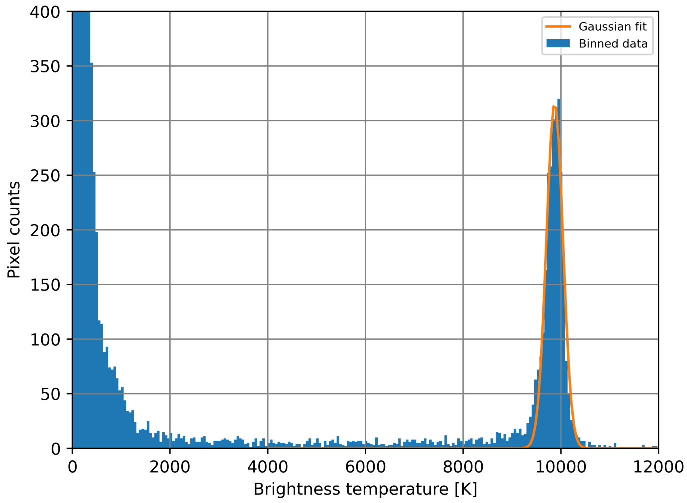

Figure 4: *Histogram of number of counts as a function of pixels, in linear scale, produced by the self-calibration process. The histogram is referred to the* 18.3 *GHz observation performed on June 23th 2018 at Medicina radio telescope. The upper part of the distribution is well fitted by a Gaussian (orange line), whose peak corresponds to the RMS value of the brightness temperature of the quiet-sun, and the width is connected with the solar activity. The low-counts tail of the quasi-Gaussian distribution in the histogram is due to the brightness gradient of the corona.*

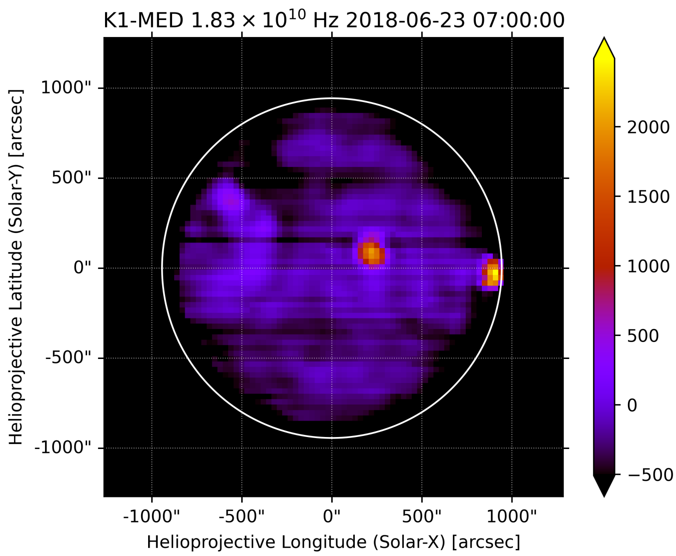

Figure 5: *Solar disk image, subtracted from the quiet-Sun level, at* 18.3 *GHz obtained with the Medicina Radio Telescope on June 23th 2018, processed with* SUNDARA *package. The Active regions SPoCA 21859 (NOAA 12715, on centre of the solar disk) and SPoCA 21840 (NOAA 12713, on right) are evident in the image. The white circle indicates the mean value of photospheric radius of the Sun $R = 695.7$ Mm [16].*

algorithms, that search patterns consistent with an elliptical 2D-Gaussian kernel:

1. method based on the DAOStarFinder class, an implementation of the DAOFIND algorithm [14];

2. AR identification based on Photutils package;

3. AR extraction based on SciPy package [19], above a specific brightness threshold (3 times the RMS of the quiet-sun level);

4. method based on SunPy package and the peak_local_max function in the scikit-image library [18].

The detected AR are modelled through an elliptical 2D-Gaussian with noise [8], where the best-fit parameters are calculated through the sequential least squares programming tools available in the Python SciPy package[7] [6]. The free parameters are the AR helioprojective coordinates (Solar-X and Solar-Y) [15], the amplitude A, the size (semiaxes of the extraction ellipse a and b), the rotation angle of the ellipse θ, and the background noise N_{bkg}. To guide the modelling, we set up as initial point the AR coordinates estimated by the initial AR detection and the minimum RMS of the quiet Sun of the solar disk. For each modelled AR, SUNDARA sets up a research region with twice the semi-axes obtained in the modelling (Fig. 6).

AR sizes larger than several times the beam size of our receivers probably represent the diameter of sources within a AR characterised by a complex morphology: to prevent this aspect, SUNDARA selects the minimum AR size detected among the same ARs identified in other solar maps of our analysis array (at same epoch and radio telescope) at different observing frequencies.

Moreover, the identified ARs are automatically associated in position with the detected ARs at other observing frequencies (Fig. 7), reported in the Heliophysics Event Knowledgebase (HEK [5])[8]. This repository of feature and event information about the Sun is based on both automated algorithms and human observers; SunPy accesses this information through the hek module[9].

SUNDARA produces a complete analysis of a solar map in a few minutes, 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 the maps (Fig. 2).

The excess brightness temperature of ARs above quiet Sun levels, T_{ex}, is trivially defined as $T_b - T_{b(QS)}$, where T_b and $T_{b(QS)}$ are the maximum brightness temperature of the AR and the quiet Sun temperature $T_{b(QS)}$, respectively. The error on T_b is provided by the calibration uncertainties ($\sim$2.5% error on average, depending on frequency) [11, 9]. Statistical errors are typically of the order of $\sim$0.1% due to very high signal-to-noise-ratio ($> 10^4$) of solar disk brightness (typical image sensitivity < 10 K).

The ARs fluxes $S_{\nu(AR)}$ (in units of sfu[10]) are calculated along the region associated with each AR detection through the integration of their brightness. Together with their

[7] http://www.scipy.org/

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

[9] https://docs.sunpy.org/en/stable/guide/acquiring_data/hek.html

[10] 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.

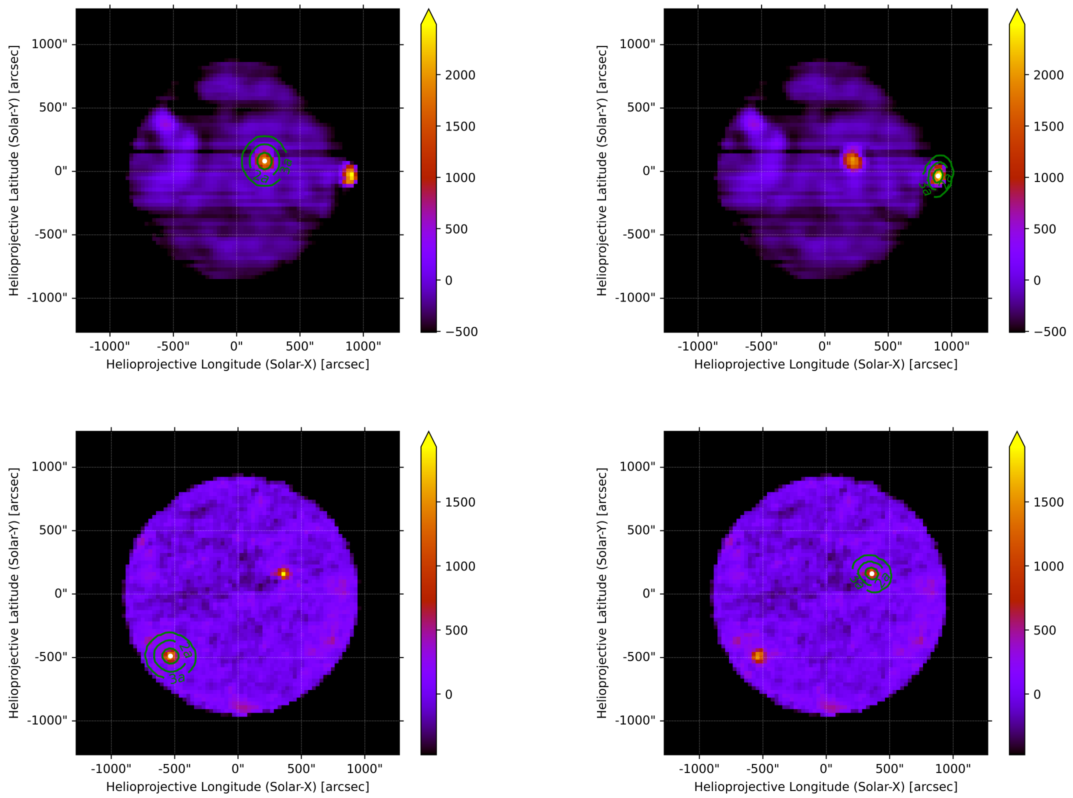

Figure 6: *Research regions (corresponding to 1, 2, and 3 times the semi-axes obtained in the modelling, green circles) detected for each detected AR with* SUNDARA *in the solar disk image (top) at* 18.3 *GHz obtained with the Medicina Radio Telescope on June* 23th *2018, and (bottom) at* 24.7 *GHz obtained with SRT on January* 28th *2020. Maps are subtracted by the Quiet-Sun level.*

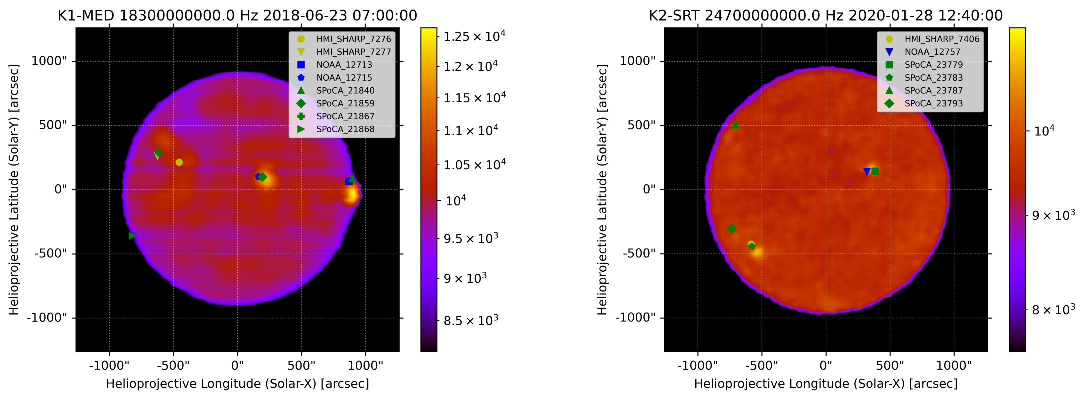

Figure 7: *Detected ARs at other observing frequencies, reported in the Heliophysics Event Knowledgebase (HEK), associated with the image of the Sun (at the same observing epoch) at (left)* 18.3 *GHz obtained with the Medicina Radio Telescope on June* 23th *2018, and (right) at* 24.7 *GHz obtained with SRT on January* 28th *2020.*

uncertainties, they are given by Rayleigh-Jeans approximation:

$$S_{\nu(AR)} = 10^{22}\frac{2k_B\nu^2}{c^2}\Omega_{pix}\sum_{pix} T_b \; [sfu], \tag{1}$$

$$\sigma_{S_{\nu(AR)}} = S_{\nu(AR)}\sqrt{(\sigma_{f_{cal}}/f_{cal})^2 + (\sigma^{stat}_{T_b}/ < T_b >)^2/N_{pix}} \sim \frac{S_{\nu(AR)}\sigma_{f_{cal}}}{f_{cal}} \; [sfu], \tag{2}$$

where $k_B = 1.38 \cdot 10^{-23}$ J K^{-1} is the Boltzmann constant, ν is the observing frequency, Ω_{pix} indicates the angular size of the map pixel in radians, N_{pix} the number of pixels associated to the AR's region characterised by $T_{ex} > 0$. $\sigma_{f_{cal}}/f_{cal}$ the calibration fractional error, and $\sigma^{stat}_{T_b}$ the statistical error corresponding to the image RMS. Finally, 10^{22} is the conversion factor from W m^{-2} Hz^{-1} sr^{-1} to sfu unit.

For the observations in which AR brightness/flux information (including upper limits) is available at two (or three) frequencies, we provided spectral index α measurements. α is calculated by knowing the relation between the flux density and the frequency $S_\nu \sim \nu^\alpha$, as follows:

$$\alpha = \frac{log(S_{\nu_1}/S_{\nu_2})}{log(\nu_1/\nu_2)} \; . \tag{3}$$

The flux density spectral index values calculated from the temperature (T_b or T_{ex}) is obtained as follows [13]:

$$\alpha = \frac{log[(T_1/T_2)(\nu_1/\nu_2)^2]}{log(\nu_1/\nu_2)} \; . \tag{4}$$

We calculated the error on α through the propagation of uncertainty on Eq. 3 (and 4):

$$\Delta\alpha = \frac{\log e}{\log(\nu_1/\nu_2)}\sqrt{\left(\frac{\Delta X_1}{X_1}\right)^2 + \left(\frac{\Delta X_2}{X_2}\right)^2} \; , \tag{5}$$

where ΔX and X are referred to the measure S_ν (or temperatures T_b and T_{ex}) and its uncertainty ΔS_ν (or ΔT_b and ΔT_{ex}), depending on the nature of the adopted physical parameter. A correct measure of α for a detected AR is based on the selection of the minimum AR size detected among the same ARs identified at the same epoch (and radio telescope) at different observing frequencies; this criterion allows to prevent possible overestimated AR sizes, probably characterised by a complex morphology.

A deep analysis (also a few hours) is possible thanks to the Python EMCEE package[11] [4], based on the Markov Chain Monte Carlo (MCMC) analysis in Bayesian approach. EMCEE is able to flush out degeneracies in the model parameters, with the aid of corner plots [3][12]. These parameters are constrained through the definition of prior distributions that encode preliminary and general information[13].

4 Test cases for SUNDARA

SUNDARA has been successfully tested on several solar maps implemented with the radio telescopes of the INAF Network (SRT and Medicina). In this technical note we report only

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

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

[13] SUNDARA considers uniform priors, but the exact ranges are still under development.

two cases as a useful reference (June 23^{th} 2018, Medicina; January 28^{th} 2020, SRT), but an updated and complete analysis of more than 150 images will be soon available [11].

The summary of our test cases is reported in Table 1; in Table 2 we report the fluxes of the detected ARs, and in Table 3 we report the spectral indices of each solar AR.

Table 1: *Summary of Medicina and SRT observations. ID indicates the identification number for each single map, where the letters M and S specify the radiotelescope (Medicina or SRT); Epoch indicates the observation date (expressed as yy-mm-dd); T indicates the acquisition time interval of the map (in units of Universal Time); ν_{obs} is the central observing frequency (in units of GHz); σ indicates the width of the Gaussian distribution in the histogram of the counts, with relative uncertainty; AR_n indicates the number of identified ARs in each solar map.*

ID	Epoch [yy-mm-dd]	T [UT]	ν_{obs} [GHz]	σ [K]	AR_n
$\#M1$	18-06-23	09:00-10:15	18.3	169.6 ± 3.2	3
$\#M2$	18-06-23	10:17-11:31	26.1	247.7 ± 4.0	3
$\#S1$	20-01-28	09:41-11:25	18.8	162.7 ± 2.8	2
$\#S2$	20-01-28	11:26-13:18	18.8	252.7 ± 3.8	2
$\#S3$	20-01-28	13:40-15:24	24.7	122.2 ± 1.0	3

Table 2: *Analysis results obtained with* SUNDARA. *ID indicates the identification number for each single map, where the letters M and S specify the radiotelescope (Medicina or SRT); ar_id indicates the AR name (if present); Epoch indicates the observation date (expressed as yy-mm-dd); T indicates the acquisition time interval of the map (in units of Universal Time);* ν_{obs} *is the central observing frequency (in units of GHz); Size indicates the AR size, at twice the fitted semi-axes level (in units of* 10^{-6} *sr);* $T_{b,tot}$ *indicates the peak of the brightness temperature for each AR (in units of K);* S_{sub} *and* S_{tot} *indicate the AR flux density of the subtracted image and the original image, respectively (in units of sfu, Eq. 1). Notes indicates further AR information: "b" indicates if the AR position is located outside of the 95%-level of the solar radius; "1,2,3,..." indicates the number of detected AR for the same observing session; "A,B,C,D,E,F" indicates the quality of the extraction region around the AR (A = good quality, F = bad quality).*

ID	*ar_id*	Epoch (yy-mm-dd)	T (UT)	ν_{obs} (GHz)	Size (sr $\cdot 10^{-6}$)	$T_{b,tot}$ (K $\cdot 10^4$)	S_{sub} (sfu)	S_{tot} (sfu)	Notes
$\#M2$	NOAA_12713, SPoCA_21840	18-06-23	10:17-11:31	26.1	0.23	1.12 ± 0.03	0.39 ± 0.01	5.13 ± 0.13	bA1
$\#M1$	NOAA_12713, SPoCA_21840	18-06-23	09:00-10:15	18.3	-	1.27 ± 0.03	0.42 ± 0.01	2.85 ± 0.07	bA1
$\#M1$	NOAA_12715, SPoCA_21859	18-06-23	09:00-10:15	18.3	1.10	1.21 ± 0.03	0.72 ± 0.02	12.17 ± 0.30	A2
$\#M2$	NOAA_12715, SPoCA_21859	18-06-23	10:17-11:31	26.1	-	1.13 ± 0.03	1.00 ± 0.02	23.38 ± 0.58	E2
$\#M1$	SPoCA_21867	18-06-23	09:00-10:15	18.3	0.80	1.06 ± 0.03	0.13 ± 0.003	8.49 ± 0.21	C3
$\#M2$	SPoCA_21867	18-06-23	10:17-11:31	26.1	-	0.99 ± 0.03	0.03 ± 0.001	15.35 ± 0.38	F3
$\#S3$	SPoCA_23783	20-01-28	13:40-15:24	24.7	1.10	1.14 ± 0.03	0.80 ± 0.02	21.00 ± 0.52	D1
$\#S1$	SPoCA_23783	20-01-28	09:41-11:25	18.8	-	1.25 ± 0.03	1.48 ± 0.04	32.36 ± 0.81	bD1
$\#S2$	SPoCA_23783	20-01-28	11:26-13:18	18.8	-	1.24 ± 0.03	0.69 ± 0.02	12.97 ± 0.32	C1
$\#S3$	NOAA_12757, SPoCA_23779	20-01-28	13:40-15:24	24.7	0.66	1.18 ± 0.03	0.52 ± 0.01	12.56 ± 0.31	C2
$\#S1$	NOAA_12757, SPoCA_23779	20-01-28	09:41-11:25	18.8	-	1.25 ± 0.03	0.71 ± 0.02	20.90 ± 0.52	C2
$\#S2$	NOAA_12757, SPoCA_23779	20-01-28	11:26-13:18	18.8	-	1.25 ± 0.03	0.49 ± 0.01	7.45 ± 0.19	D2
$\#S3$	SPoCA_23787	20-01-28	13:40-15:24	24.7	0.34	1.02 ± 0.03	0.14 ± 0.003	6.35 ± 0.16	bC3
$\#S1$	SPoCA_23787	20-01-28	09:41-11:25	18.8	-	< 1.04	< 0.11	< 10.16	u
$\#S2$	SPoCA_23787	20-01-28	11:26-13:18	18.8	-	< 1.07	< 0.08	< 3.54	u

Table 3: *Spectral indices obtained with* SUNDARA. α_{T_b}, α_{sub}, *and* α_{tot} *indicate the spectral indices referred to* $T_{b,tot}$, S_{sub}, *and* S_{tot}, *respectively. See the caption of Table 2 for a full description of the other parameters.*

ID	*ar_id*	Epoch (yy-mm-dd)	T (UT)	ν_{obs} (GHz)	Size (sr $\cdot 10^{-6}$)	α_{T_b}	α_{sub}	α_{tot}
$\#M2$	NOAA_12713, SPoCA_21840	18-06-23	10:17-11:31	26.1	0.23	1.65 ± 0.10	0.44 ± 0.10	1.66 ± 0.10
$\#M1$	NOAA_12713, SPoCA_21840	18-06-23	09:00-10:15	18.3	-	-	-	-
$\#M1$	NOAA_12715, SPoCA_21859	18-06-23	09:00-10:15	18.3	1.10	1.81 ± 0.10	1.36 ± 0.10	1.84 ± 0.10
$\#M2$	NOAA_12715, SPoCA_21859	18-06-23	10:17-11:31	26.1	-	-	-	-
$\#M1$	SPoCA_21867	18-06-23	09:00-10:15	18.3	0.80	1.80 ± 0.10	-1.10 ± 0.10	1.67 ± 0.10
$\#M2$	SPoCA_21867	18-06-23	10:17-11:31	26.1	-	-	-	-
$\#S3$	SPoCA_23783	20-01-28	13:40-15:24	24.7	1.10	1.65 ± 0.13	0.45 ± 0.13	-1.59 ± 0.13
$\#S1$	SPoCA_23783	20-01-28	09:41-11:25	18.8	-	-	-	-
$\#S3$	SPoCA_23783	20-01-28	13:40-15:24	24.7	1.10	1.70 ± 0.13	0.69 ± 0.13	1.77 ± 0.13
$\#S2$	SPoCA_23783	20-01-28	11:26-13:18	18.8	-	-	-	-
$\#S3$	NOAA_12757, SPoCA_23779	20-01-28	13:40-15:24	24.7	0.66	1.79 ± 0.13	1.34 ± 0.13	-1.86 ± 0.13
$\#S1$	NOAA_12757, SPoCA_23779	20-01-28	09:41-11:25	18.8	-	-	-	-
$\#S3$	NOAA_12757, SPoCA_23779	20-01-28	13:40-15:24	24.7	0.66	1.78 ± 0.13	1.29 ± 0.13	1.91 ± 0.13
$\#S2$	NOAA_12757, SPoCA_23779	20-01-28	11:26-13:18	18.8	-	-	-	-
$\#S3$	SPoCA_23787	20-01-28	13:40-15:24	24.7	0.38	> 1.84	> 0.90	> 2.14
$\#S2$	SPoCA_23787	20-01-28	11:26-13:18	18.8	-	-	-	-
$\#S3$	SPoCA_23787	20-01-28	13:40-15:24	24.7	0.38	> 1.95	> 3.84	> -1.72
$\#S1$	SPoCA_23787	20-01-28	09:41-11:25	18.8	-	-	-	-

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