"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

Project (Grant) Number:	824135
Project Acronym:	SOLARNET
Project Title:	Integrating High Resolution Solar Physics

Document Details	
Document Title:	Report on the inventory of existing software and expressed needs for solar physics data tools
Prepared by (Institution's Name):	The University of Sheffield (USFD)
Work Package (WP) Number & Title:	WP2: Coordination for improved exploitation of solar physics infrastructure
Sub-Work Package (sub-WP):	WP2.2.3
Deliverable Number & Title:	D2.17 Report on the inventory of existing software and expressed needs for solar physics data tools
Serial Number of Deliverable:	D23
Document Code: (inserted by project office)	D2.17_Version 1.0
File Name: (inserted by project office)	SOLARNET_D2.17_V1.0_SPDT_Public_20200629
Date Uploaded: (inserted by project office)	June 29th, 2020

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

SOLARNET

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

AUTHORS/ CONTRIBUTORS LIST (In the order listed in the proposal)

Name	Function	Organization
R. Erdelyi	Lead of WP2.2.3	USFD
M. Löfdahl	Collaborator	SU
M. Carlson	Collaborator	UiO
M. Mathioudakis	Collaborator	QUB
M. Sobotka	Collaborator	ASU
A. J. Leonard	Collaborator	Aperio

APPROVAL CONTROL FROM sub-WP and WP LEAD

Control	Name	Organization	Function	Date
Prepared	R Erdelyi	USFD	Lead of WP2.2.3	May 28th, 2020
Prepared	M. Löfdahl	SU	Collaborator	June 12th, 2020
Approved	D. Kiselman	SU	WP2 lead	June 15th, 2020

ADMINISTRATIVE APPROVAL CONTROL FROM PROJECT OFFICE

Control	Name	Organization	Function	Date
Approved	T. Som	KIS	Project Manager	June 29th, 2020
Approved	R. Schlichenmaier	KIS	Project Coordinator	June 29th, 2020
Authorized	M. Roth	KIS	Project Scientist	June 29th, 2020

HISTORY OF DOCUMENT CHANGES

Issue	Date	Change Description
Version 1.0	June 15th, 2020	Initial Issue

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

“This project has received funding from the European Union’s Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)”

Table of Contents

List of Abbreviations

ASDA: Automated Swirl Detection Algorithm
CDT: Core Development Tools
CGST: Chinese Giant Solar Telescope
DKIST: Daniel K Innoyue Solar Telescope
EST: European Solar Telescope
MONAMI: Mapping of Non-potentiAl Magnetic fIeld
NLST: national Large Solar Telescope

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

Objectives

This report determines the needs, availability, and future desired directions of computational, visualisation and analysis tools. It focuses towards the composition an inventory of existing tools relevant in particular for WP5 with the focus towards supporting the development and realisation of the European Solar Telescope (EST).

Description of work

WP2.2.3. is about the coordination of development of software tools for solar physics. An inventory will be made for the needs, availability, and future desired directions of computational, visualisation & analysis tools. Together with ongoing discussions this will direct the activities in WP5.

Deliverable

Report on the inventory of existing software and expressed needs for solar physics data tools.

Needs

The combined interplay of the Sun's complex, highly inhomogeneous and stratified magnetic field and the ionized hot plasma this field is embedded provides a variety of exotic plasma dynamics, including highly subtle processes that change the field topology (e.g. magnetic reconnection), wave processes that enable the transport of momentum and energy between various distinct regions of the Sun at a wide range of spatio-temporal and spectral scales. A considerable effort both in terms of developing solar facilities (e.g., observatories, data centres, etc.) have been devoted over the last several decades, on the ground and in space, that have contributed to a significantly improved understanding of the energy and mass transport processes in the Sun and the Sun-earth system. These developments have resulted in state-of-the-art facilities (on the ground, e.g., BBSO, DOT, DST, Gregor, VTT, SST, Themis, and more recently DKIST while in space SOHO, TRACE, Hinode, RHESSI, STEREO, and more recently SDO, SPP, Solar Orbiter to name a few) that all provide a huge amount of data well into Terra Byte if not more. It is identified that beside the need of instrumental development a key bottleneck in progress may be our limitations to store, transport, visualize and analyse these data. DKIST now and EST, NLST or CGST in the near future, thanks to their ultra-high resolution, will deliver data of the order of Pb daily. Taking stock of the underlying technology development (e.g. adaptive optics, new spectrographs, latest CPU/GPU or new methods of data storage) is beyond the scope of this project. However, addressing in a comprehensive way the current availability and future needs of software and analysis tools is the remit of this report. In particular, as EST is still on the engineering drawing desk in terms of realization, therefore a stock-tacking exercise is seen useful not just for WP5 of SOLARNET but for the EST developers.

Availability

A1) In terms of *solar data analysis and visualization,* the major overall driving and available software packages for both ground-based and space-born solar data are *SolarSoft* and *SunPy*. A wide range of specific tools were developed as part of the DKIST project that are seen as good impetus to be generalized to further upcoming ultra-high resolution telescopes like EST, NLST (India), CGST (China, Deng et al. 2011). A range of focused tools have been delivered or are under development as part of this effort. For a more complete list see the (Verwichte et al. 2018). The list includes generic instrumental cookbooks, visual optimisation code, Fourier filtering algorithms for spectral filtering, advanced filtering packages designed to enhance solar structures in images and oscillatory features in time-space data, tools to analyse transverse motions of magnetic structures, tools to detect spicule oscillations and vortex flows in the solar atmosphere, tool to analyse the dynamics of thin chromospheric magnetic flux tubes in

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

3D, pattern recognition package using machine learning, tool aiding the analysis and time-normalisation processing of optical flow, etc.

A2) In terms *of solar modelling and computing* (whether numerical or data-driven) a number of state of the art efforts have been identified that can provide often beyond the currently available temporal, spatial or spectral resolutions an insight into the physical processes taking place in various regions of the Sun. It is not feasible to give an account of all such efforts, but leading compute modelling includes: AWESOM, Bifrost, ENLIL, Euphoria, Lare3d, MPI-AMRVAC, MURAM, Pencil, SAC, SMAUG, WSA-ENLIL. These codes employ the latest CFD techniques, optimization and architecture solutions (e.g. MPI, adaptive grids, CUDA, etc…).

Future directions

The future directions will strongly depend on

i) how major ground-based facilities, e.g. DKIST or EST will develop. The instrument suit of DKIST is already in place and first-light images released in January 2020 (see here), while EST has released its SRD with a comprehensive list of potential observing sequences (Schlichenmaier et al 2019) that will be the basis to determine its instrument suits. In this regard a Technical Review Panel was formed in early 2020 and progress is ongoing; and

ii) how computing facilities and the underlying technology will develop. Given the massive amount of foreseeable data produced by DKIST, EST or space-borne solar facilities (SDO, IRIS, Solar Parker Probe, Solar Orbiter, Aditya-L1, etc.) there is a very strong necessity for establish easy-to-access PB order of amount of data with most likely on-site analysis. It may not be seen practical or even feasible to move around such amount of data for processing, visualising and analysis. In terms of EST, a Data Centre is a potential manifestation to cater for these future needs and defining its capabilities and capacity is ongoing. User would get accounts and disk space to use visualisation tools, upload software and carry out their science analysis at the data centre. This will avoid moving the same Tb size datasets around the Globe. This is an approach that begins to emerge in some night time facilities.

Image reconstruction

Image reconstruction with methods based on multi-frame blind deconvolution is based on fitting a model of the image formation through the atmosphere and instrumentation. Some of the problems with those methods come from mismatches between the model and reality. Anisoplanatism (spatial variations of atmospheric wavefront aberration) are usually modelled as isoplanatic subfields that are restored independently and then mosaicked. In reality, spatial variations appear on scales smaller than subfield sizes that are realistic to process independently due to insufficient information content. Wavefront aberrations are modelled as sums of a usually fairly small number of low-order modes, while in reality aberrations consist of many more, higher-order modes (with diminishing magnitude) than can realistically be sensed from the often low-contrast image data in high-resolution solar observations. Addressing those deficiencies are part of the WP5 effort.

Hardware

During the last decade, deep learning has emerged as a powerful tool to extract relevant information from observations. Using very deep and complex neural networks one can improve the performance of specific tasks, being much better or faster than the classic algorithms. Among them one can find fast image reconstruction, 3D inversion of the Stokes parameters, noise reduction in observational data, classification and tracking of solar features, etc. The time-consuming part of these algorithms is the training part, which can be reduced by running the process on a GPU. As these techniques will be used more frequently in the

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

future and new ones will appear, the use of GPUs will likely increase. This is not a hard requirement, as parallelization of the training process on multiple modern CPUs could be similarly effective.

Software

During the last decade, Python has become one of the most popular languages in our field. After many years, we have a very consolidated solar community with robust programs written in the proprietary language IDL. A new effort to transform older routines into Python and create new ones for the current/future facilities is also necessary. This effort will also give the possibility to do science to other people that do not have resources for paying software. This has been one of our motivations to start a Python library or share our software in a public repository.

Inventory

Listed by contributors with relevance to WP5.

SU contribution

Observational data processing

- SSTRED: A data pipeline for SST/CRISP and SST/CHROMIS. Inputs raw observational data and associated calibration data, outputs science-ready data in FITS files with rich meta data (Löfdahl et al. 2018, de la Cruz Rodriguez et al. 2015, 2017).
- *redux*: Image restoration and wavefront estimation with multi-object multi-frame blind deconvolution (MOMFBD) and phase diversity. Designed to measure and correct for optical aberrations from instrumentation as well as from turbulence in the Earth's atmosphere (Löfdahl 2002, Löfdahl et al. 2018, van Noort et al. 2005).
- *CRISPEX*: The CRIsp Spectral Explorer, a data cube browsing and analysis code for data from SST/CRISP, SST/CHROMIS, as well as IRIS (Vissers et al. 2012)
- *ISPy*: A Python library of commonly used tools at the Institute for Solar Physics (Stockholm University). It was designed to cover the post-pipeline processing and alignment of SST data, radiative transfer calculations, and inversion pre- and post-processing, among others. The library is in an early release allowing us to read/write SST data with previous and SOLARNET format, spectral calibration, magnetic field estimation, and other visualization tools.

Atmospheric inversion codes

- *STiC*: a LTE/NLTE inversion code by de la Cruz Rodriguez et al. (2019) (https://github.com/jaimedelacruz/stic)
- *MINE*: a Milne-Eddington based inversion code by de la Cruz Rodriguez *(https://github.com/jaimedelacruz/MINE)*
- *A spatially constrained weak field approximation code*: Morosin et al (in preperation).

Deep learning

- *Solar image denoising with convolutional neural networks*: A neural network that is capable of recovering weak signals under a complex noise corruption (including instrumental artifacts and non-linear post-processing). The performance of this method has been demonstrated in a recent publication by Díaz Baso et al. (2019). In that publication we show examples of the improvement in typical signals obtained with the Swedish 1-meter Solar Telescope. The presented method can recover weak signals equally well no matter what spectral line or spectral sampling is used. It is especially suitable for cases when the wavelength sampling is scarce. The code is available in a Github repository.
- *Stokes Inversion based on Convolutional Neural Networks*: Spectropolarimetric inversions to two-dimensional fields of view often require the use of supercomputers with parallelized inversion codes. We have developed a new inversion code (Asensio Ramos, A. and Diaz Baso 2019) based

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

on the application of convolutional neural networks that can quickly provide a three-dimensional cube of thermodynamical and magnetic properties from the interpretation of Stokes profiles. It provides several key improvements: it is around one million times faster, it returns the physical properties of the region in geometrical height, it provides quantities that cannot be obtained otherwise (pressure and Wilson depression) and the inferred properties are decontaminated from the blurring effect of the instrumental point spread functions. The code is provided in a Github repository.

- *Quick image restoration based on Deep learning*: A module for quick image restoration has been developed and embedded in the SSTRED reduction pipeline to be able to produce quick-look movies that provide a better view of the target and a better indication of the image quality after MOMFBD reconstruction. This module is based on the neural network reconstruction presented by Asensio Ramos et al. (2018), which gives both fast and good quality reconstructions. For this module, the network has been modified to improve its performance (speed, memory usage, etc.). This module was also created with the idea of adapting the network in the future to provide almost real-time reconstructed images on the telescope.

UiO contribution

- *Multi*: (to be replaced by a GitHub repository in autumn 2020) is a multi-level non-LTE spectrum synthesis code that has been in the public domain since 1986. It is still a workhorse code many places, although a number of useful features are missing from the standard version (PRD, blends, polarisation).
- *RADYN*: a 1D radiation hydrodynamic code that solves the equations of conservation of mass, momentum, energy and charge together with the rate equations in full non-LTE for any number of atomic species on an adaptive grid (Carlsson & Stein 1992, 1995, 1997). Energy may be fed into the system through a prescribed source term as function of time and space or as an electronic beam with a given spectral index, cut-off energy and total energy flux. The electron beam energy transport is solved through a Fokker-Planck treatment (Allred et al 2015). The code will be made open access through a GitHub repository in 2020.
- *Bifrost*: (Gudiksen et al 2011) a massively parallel 3D Radiation MHD code with extended and flexible physics modules capable of treating detailed radiative transfer including scattering in the photosphere/lower chromosphere, conduction along field lines, approximate non-LTE radiative losses in the chromosphere, thin radiative losses in the corona and non-equilibrium ionization of hydrogen and helium. It is also possible to include ion-neutral effects through a generalized Ohm's law as a single fluid. Efforts are ongoing to release Bifrost in the pubic domain.
- *Helita*: a Python library for solar physics focused on interfacing with code and projects from the (ITA) and the (RoCS) at the . The name comes from Helios + ITA. The library is a loose collection of different scripts and classes with varying degrees of portability and usefulness. For more details including installation instructions, please see the documentation here.

QUB contribution

- *Co-alignment and visualisation tool* for high-resolution multi-instrument and simulated data. For details see the reporting on WP5.

ASU contribution

For details see the reporting on WP5.

- *KAPPA* software package: Description of particle energies in the solar corona and flares by the non-thermal Kappa-distribution. Compatibility with the atomic-data database CHIANTI.
- *FLARIX*: Solar radiative-hydrodynamics non-LTE code. Modelling of chromospheric response to impacting particle beams. Case studies and simulations of solar flares.

"This project has received funding from the European Union's Horizon 2020 research and innovation programme for the period January 2019 until December 2022 under Grant Agreement No 824135 (SOLARNET)"

Aperio contribution

- *A full solar image calibration pipeline* is being developed for the Visible Tunable Filter (VTF) on DKIST. This is being written in Python and will use packages and tools already existing in the Python in astronomy community where possible. The aim is for this pipeline to be modular and sufficiently general-purpose that it can easily be made to work for other ground-based solar telescopes.

USFD contribution

Atmospheric tools

- *Mapping of Non-potentiAl Magnetic fIeld (MONAMI)*: MONAMI is about processing and the construction of 3D magnetic field structure of solar active region (AR).
- *Automated Swirl Detection Algorithm v2 (ASDA v2)*: ASDA aimed to be used for automatic swirl/vortex detection from observational images or computational modelling of the solar atmosphere.

Core Development Tools (CDT)

- *Python converting output of MONAMI into NDCube*: This generic modul is useful when converting output of MONAMI into NDCube, access it here on Github.
- *Improved NDCube package*: Supporting NDCube for loading coordinate information from wider sources of data than just space-based observations in FITS files.
-

Conclusions

WP2.2.3. is a coordinated effort about understanding the needs, availability and future desired directions of the software tool developments for solar physics. An initial inventory is made with a focus on the EST overall project. The needs and future directions were identified and are outlined. WP2.2.3 is complementary to the activities of WP5 and should therefore be read, understood and interpreted in conjunction with the report on WP5.

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

References

Allred, J.C., Kowalski, A.F., Carlsson, M., "A Unified Computational Model for Solar and Stellar Flares", ApJ, 809:104, 2015

Asensio Ramos, A. and Diaz Baso, C., "Stokes Inversion based on Convolutional Neural Networks", 2019

Asensio Ramos A. et al., "Real-time, multiframe, blind deconvolution of solar images", A&A, 620:73, 2018

de la Cruz Rodriguez, J. et al., "CRISPRED: A data pipeline for the CRISP imaging spectropolarimeter", A&A, 573:40, 2015

Carlsson, M. & Stein, R.F., "Non-LTE radiating acoustic shocks and CA II K2V bright points". ApJ, 397:L59, 1992

Carlsson, M. & Stein, R.F., "Does a nonmagnetic solar chromosphere exist?", ApJ, 440:L29, 1995

Carlsson, M. & Stein, R.F., "Formation of Solar Calcium H and K Bright Grains", ApJ, 481:500, 1997

de la Cruz Rodriguez, J. et al., "CRISPRED: CRISP imaging spectropolarimeter data reduction pipeline" Astrophysics Source Code Library, record ascl:1708.003, 2017

de la Cruz Rodriguez, J. et al., "STiC: A multiatom non-LTE PRD inversion code for full-Stokes solar observations", A&A, 623:74, 2019

Deng, Y.Y. and the CGST team, "Introduction to the Chinese Giant Solar Telescope", ASI-CS 31, 36 2011

Díaz Baso, C. et al. "Solar image denoising with convolutional neural networks", A&A, 629:992019

Gudiksen, B.V. et al. "The stellar atmosphere simulation code Bifrost. Code description and validation", A&A, 531A:154, 2011

ISPy Documentation, https://github.com/ISP-SST/ISPy

Korsos M.B., Liu J., Erdelyi, R. et al., "MONAMI v1", 2019

Liu J. et al., "Automated Swirl Detection Algorithm (ASDA) and Its Application to Simulation and Observational Data", ApJ, 872:22, 2019

Liu J. et al., "ASDA v2", 2020

Liu J. Mumford S. and Erdelyi, R., "Python converting output of MONAMI into NDCube", 2020

Löfdahl, M. "Multi-frame blind deconvolution with linear equality constraints", SPIE, 4792, 146, 2002

Löfdahl, M. et al., "SSTRED: A data-processing and metadata-generating pipeline for CHROMIS and CRISP", 2018

Schlichenmaier R. et al., "Science Requirement Document (SRD) for the European Solar Telescope (EST)", 2nd edition, 2019

SolarSoft, https://www.lmsal.com/solarsoft/

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de

SunPy, https://sunpy.org

The SunPy Community, "The SunPy Project: Open Source Development and Status of the Version 1.0 Core Package", ApJ, 890:68, 2020

van Noort et al., "Solar Image Restoration By Use Of Multi-frame Blind De-convolution With Multiple Objects And Phase Diversity ", Solar Phys, 229, 191, 2005

Verwichte E. et al., "DKIST STFC PPRP Work Package 2", 2018

Vissers, G. and van der Voort, R., "Flocculent Flows in the Chromospheric Canopy of a Sunspot", ApJ, 750:22, 2012

Leibniz-Institut für Sonnenphysik (KIS)
Schöneckstr. 6, 79104 Freiburg Germany
Tel.: +49-761-3198-224; Email: SOLARNET-office@leibniz-kis.de