Jupiter radio emission probability tool

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Jupiter is a source of intense radio emissions in the decametric wavelength range observable from ground (above ~10 MHz) and from space (down to a few kHz). The strong anisotropy of the Jovian radio sources results in characteristic shapes in the temporal-spectral domain, which can be used to identified the various types of Jovian radio components. The *Jupiter Probability Tool* provides users with Jovian radio emission observability predictions, depending on the observers location, and the radio emission class. The application can be used for observation planning or data analysis for ground or space observations.

KEYWORDS

jupiter, radio emissions, space physics, online application, observation planning, python

1 Introduction

Jupiter low frequency radio emissions have been studied since their discovery (Burke and Franklin, 1955), with ground (from 10 to 40 MHz) and space observatories (down to a few kHz), the ground based observations being limited by the ionospheric cutoff at ~10 MHz. The Jovian radio spectrum displays several components, which can be identified in dynamic spectra (time series of spectra), thanks to their temporal-spectral arc-shaped characteristic features (see, e.g.: Zarka, 2000; 2007). Moreover, a subset of Jovian radio components are driven by the interaction between the Jovian magnetic field and the Galilean moons, specifically with the moon Io (Bigg, 1963), but also with Europa and Ganymede (Louis et al., 2017a; Zarka et al., 2018a). The arc-shaped temporal-spectral geometry is a consequence of the radio emission mechanism, which produces a strongly anisotropic beaming pattern. Hence the observer's location is a key parameter for prediction the observability of Jovian radio emissions. Jupiter observation probability maps have been produced with the first published catalogues (see e.g.: Bigg, 1963; Leblanc et al., 1981), relating the observer's longitude in the Jovian System III frame (Higgins et al., 1997) and the phase of Io.

Planning or analysing Jupiter radio observations thus requires to know the observation geometry: observation date, observer's location and phase of the Jovian moons. In this article, we present an online application providing the probability of observing Jovian radio components depending on the observation and Jovian system geometries.

2 Use cases and requirements

The first use case is the analysis of a Jupiter low frequency radio observation. As presented in the introduction section, the interpretation of Jupiter radio emission observations requires an detailed knowledge of the geometry of the Jovian system, together with the observer's location. The observation configuration shall be displayed in a two-dimensional diagram with axes being (a) the longitude of the observer (usually in Jupiter system III longitude) also known as "Central

Meridian Longitude" (or CML), and (b) the selected Moon phase with respect to the observer. Such a diagram is referred to as a "Phase-CML" map. Many Phase-CML maps have been published (see, e.g., Leblanc et al., 1981; Marques et al., 2017; Zarka et al., 2018a). Comparing the selected observation configuration with Phase-CML maps greatly facilitates the Jupiter decametric radio emission observation interpretation. A second critical aspect of the Jovian radio emissions is their shape in the temporal-spectral domain. Comparing the observed shape with predicted ones would also strengthen the scientific interpretation (see, e.g., Louis et al., 2017b).

The second use case is the preparation of a Jupiter low frequency radio observation. The same geometry configuration display against Phase-CML maps allows to select observation times with higher probability of detecting the studied radio component. Furthermore, in order to prepare a ground based observation, the knowledge of Jupiter's elevation as seen from the observer's location is also required.

A series of design requirements has been derived from the two use cases.

- *Time range*: The observation time (or time range) shall be configurable.
- *Predefined observer*: Space missions with a low frequency instrument (e.g., Cassini, Juno, Wind, STEREO-A, STEREO-B, Galileo...), as well as major ground based low frequency radio observatories (e.g., Long Wavelengths Array, Nançay Decameter Array...) shall be easily configurable.
- *Custom ground-based observer*: For ground based observation, it shall be possible to set the location of an observatory (e.g., for radio amateur observatories).
- *Jovian Moon Control*: In the recent studies of Jovian radio emissions, Europa and Ganymede controlled radio emissions have been reported (Louis et al., 2017a; Zarka et al., 2018a) in addition to the long-studied Io-controlled emissions. Control by Callisto and Amalthea are also mentioned in some publications (Marques et al., 2017; Zarka et al., 2018a). The interface shall allow users to select the moon of interest (i.e., Io, Europa, Ganymede, Callisto and Amalthea).
- *Phase-CML maps*: The various published probability or occurrence Phase-CML maps shall be available for comparison (Lamy et al., 2022), which includes Phase-CML maps from Leblanc et al. (1993); Louis et al. (2017a); Marques et al. (2017); Zarka et al. (2018a,b); Jácome et al. (2022) at the time of writing.
- *Observational geometry*: The observational geometry shall be displayed on top of a selected Phase-CML map.
- *Jupiter elevation*: The elevation of Jupiter shall be displayed on the interface in a way the user can tell if the planet is observable at a given time.
- *Dynamic Spectra modeling*: An estimated model of the observed Jovian dynamic spectrum shall be available.

3 Existing tools

We have identified a set of existing tools serving the identified needs (observation planning and observation interpretation).
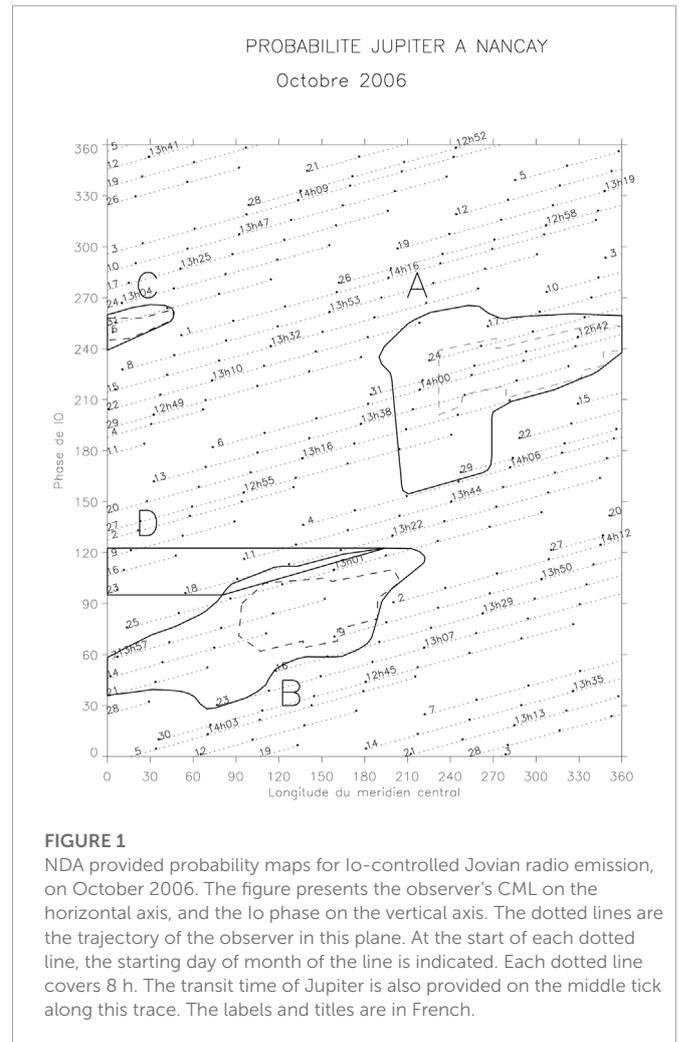
FIGURE 1
NDA provided probability maps for Io-controlled Jovian radio emission, on October 2006. The figure presents the observer's CML on the horizontal axis, and the Io phase on the vertical axis. The dotted lines are the trajectory of the observer in this plane. At the start of each dotted line, the starting day of month of the line is indicated. Each dotted line covers 8 h. The transit time of Jupiter is also provided on the middle tick along this trace. The labels and titles are in French.

3.1 Nançay decameter array probability maps

The Nançay Decameter Array (NDA, Lamy et al., 2017) is a phased array located in Nançay Radioastronomy Observatory (ORN), routinely observing Jupiter and the Sun. In addition to the data products[1], the NDA team is providing its users with a series of monthly Io Phase-CML probability maps, as well as the time of the Jupiter transit at the observer's location, as shown in **Figure 1**.

3.2 Radio jupiter pro

The Radio Sky Publishing[2] team developed tools to help the preparation of Jupiter radio observation, in the frame of the RadioJOVE citizen science project (Thieman et al., 2006; Fung et al., 2020). The *Radio Jupiter Pro* application[3] specifically provides Io Phase-CML probability map, plots indicating the elevation of Jupiter

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1 NDA propability maps: https://realtime.obs-nancay.fr/dam/data_dam_affiche/data_dam_affiche.php?lang=en&planete=jupiter&mode=proba

2 Radio Sky Publishing: https://radiosky.com/softwarehome.html

3 Radio Jupiter Pro: https://radiosky.com/rjpro3ishere.html
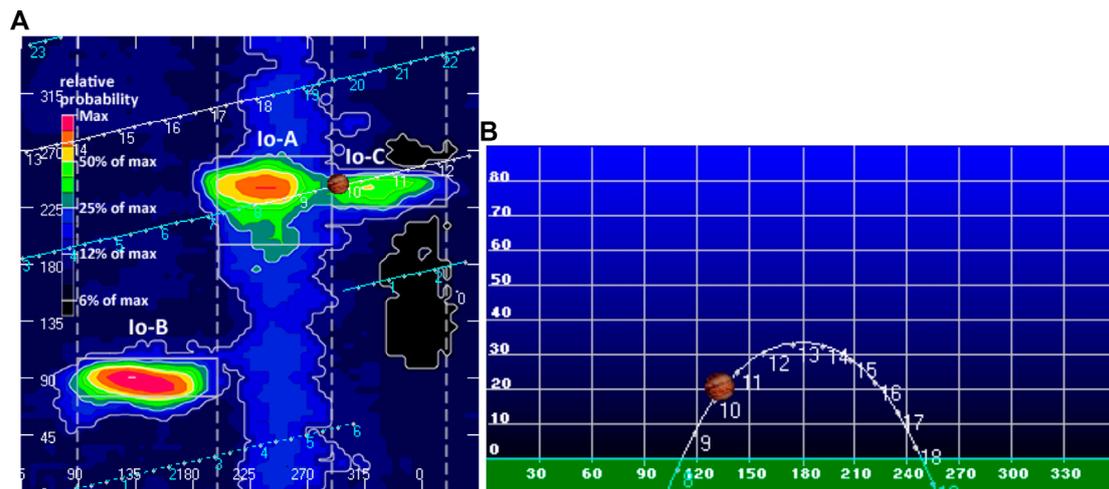
FIGURE 2
Radio Jupiter Pro features: **(A)** Io Phase-CML probability map with the observer's location marked with the Jupiter planet symbol; **(B)** elevation of Jupiter at the location of the observer. Tick marks are labelled every hour on the tracks of Jupiter on each panel.

and the Sun at the observer's location, as well as their location within the antenna beam, when this information is configured. See **Figure 2**.

3.3 Jupiter radio map

Jupiter Radio Map[4] is a java based application providing the Jovian radio observation probability, in an Io Phase-CML map. This application has been developed by a Japanese team (Kochi National College of Technology, Kochi). The tool displays an Io Phase-CML map, overlaid with the trace of the observational geometry, as selected on the user interface. It also used to be published as an iOS application.

3.4 ExPRES

The ExPRES (Exoplanetary and Planetary Radio Emission Simulator, Louis et al., 2019) is a radio observation modeling code dedicated to planetary radio emissions. It allows to construct dynamic spectra predictions, for an observation geometry and a set of radio emission conditions.

4 Online application

The "Jupiter Probability Tool" application has been designed following the requirements presented in **Section 2**. The tools cited in **Section 3** are already implementing part of project requirements. Hence, our application's graphical user interface implements some interface features found in existing tools (e.g., the location of Jupiter on the Phase-CML map, similarly to the Radio Jupiter Pro tool, as shown in **Figure 2**). However, since the previous tools are not open source, none of their code have been reused.

The application is using the SPICE kernel system (Acton et al., 2018) for computing observational and planetary ephemerides. It also displays contextual data, when available, such as observational data (e.g., from the NDA database) and pre-computed modeled data from the ExPRES modeling tool.

The application has been developed as a joint project between the MASER (Measuring, Analysing and Modeling of Emissions in the Radio range) service (Cecconi et al., 2020), and the NDA team (Lamy et al., 2017), with support of PADC (Paris Astronomical Data Centre).

4.1 Graphical user interface

Figure 3 shows a screenshot of the tool user interface. The tagged elements of this interface are described in **Table 1**. The online Jupiter Probability Tool application (Aicardi et al., 2022) is currently available at: https://jupiter-probability-tool.obspm.fr.

4.2 Development details

The application is developed in python, using the *flask*[5] web development library (Grinberg, 2018). The Solar System bodies and spacecraft ephemerides are retrieved using the *python-webgeocalc*[6] library, accessing a dedicated WebGeoCalc server (Acton et al., 2018) installed at the Observatoire de Paris. That server is configured to serve locally SPICE kernels for NASA, ESA and JAXA space mission. The NDA Jupiter data are retrieved using the *das2* (Piker, 2017) protocol, connecting to a *das2* server implemented and maintained by the Nançay Data Centre (CDN), at the Nançay Radio Observatory (ORN). The ExPRES simulation runs are retrieved from a local

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4   Jupiter Radio Map: http://jupiter.kochi-ct.jp/jrm/

5   flask: https://flask.palletsprojects.com/en/2.2.x/

6   Python-Webgeocalc: https://webgeocalc.readthedocs.io/en/latest/
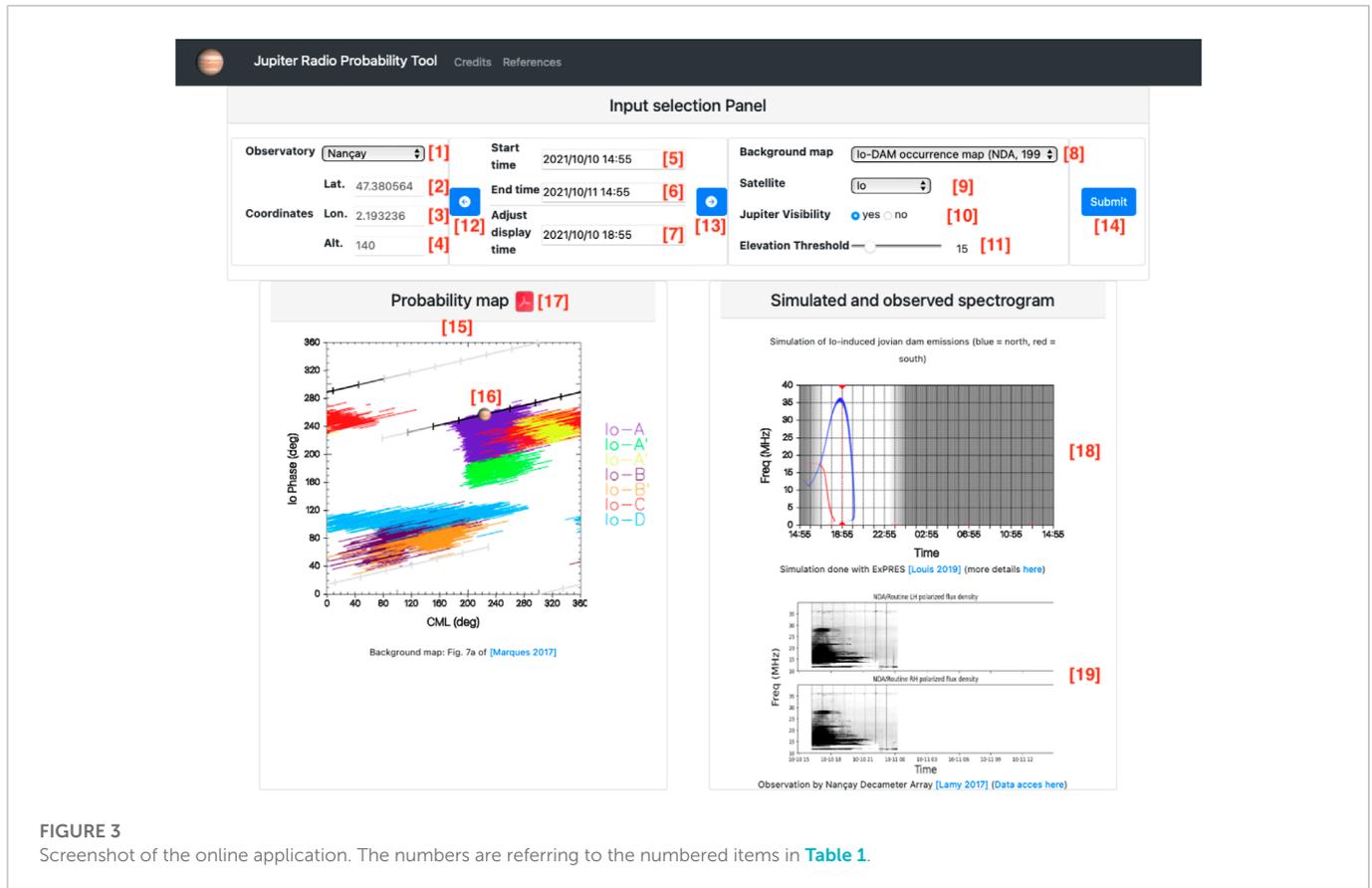
FIGURE 3
Screenshot of the online application. The numbers are referring to the numbered items in **Table 1**.

server as CDF[7] files, and are accessed using the *spacepy. PyCDF* (Niehof et al., 2022) module. The application also uses the *Pillow*[8], *numpy* (Harris et al., 2020), *astropy* (The Astropy Collaboration et al., 2018), *matplotlib* (Hunter, 2007) and *sqlalchemy* (Bayer, 2012).

4.3 Ephemerides computation

The observational geometry is computed in a two-step process. First the location of the observer is retrieved with a *STATE_VECTOR* query to the WebGeoCalc server, using the *LATITUDINAL* representation (providing latitude, longitude and distance in the selected frame), the *IAU_JUPITER* reference frame, and the aberration correction set to *CN + S* (see WebGeoCalc documentation for details). In the following listings, we assume the `timestamp` variable is a iterable containing the list of times to be used for computation (list of `datetime.datetime` objects). The `kernels` variable contains the list of meta-kernels to be usedfor the current computation. For Earth-based observatories, the *Solar System Kernels* are selected. For space mission, the specific meta-kernel has to added. Finally, the `observer` variable contains the observer's name.

```
1  from webgeocal import Calculation
2  import numpy as np
```

```
3   API = "https://voparis-webgeocalc2.obspm.fr/geocalc/
        api/"
4   calc_jupiter = Calculation(
5       kernels=kernels,
6       api=API,
7       times=[timestamp.isoformat() for timestamp in
        timestamps],
8       calculation_type="STATE_VECTOR",
9       target="JUPITER",
10      observer=observer,
11      aberration_correction="CN+S",
12      reference_frame="IAU_JUPITER",
13      state_representation='LATITUDINAL',
14      verbose=False
15  )
16  res_jupiter = calc_jupiter.run()
17  cml = (180-np.array(res_jupiter.get("LONGITUDE")))
        %360
18  date_jupiter = res_jupiter.get("TIME_AT_TARGET")
```

Listing 1: First State Vector query to Webgeocalc: computing *CML* and *time at target*.

The CML of the observer is then:

$$\text{CML} = (180 - \text{Long}_{obs}) \bmod 360 \qquad (1)$$

the result of this call also provides a *TIME_AT_TARGET*. The second query retrieves the location of the selected moon in the *IAU_JUPITER*

TABLE 1 Features of the application graphical user interface, with their type. *List* items are drop-down menus with predefined values. *Number* items are text boxes with decimal numbers input. *Epoch* items are text boxes with date and time input. *Switch* items are buttons to activate a feature. *Button* items are used to trigger an action. *Display* items are showing the result of the query. *Cursor* items are actionable objects allowing to select a location within a range.

Tag	Type	Description
1	List	*Observatory selection*: A list of predefined observatories. At the time of writing of the paper, the list of observatories is: NDA (Nançay Decameter Array, Nancay, France), UTR-2 (Kharkiv, Ukraine), Iitate (Japan), LWA (Long Wavelength Array, New Mexico, United States), I-LOFAR (Irish LOFAR station), and the Juno spacecraft. In order to manually enter the location of an observatory, use the "Custom (Earth-based)" entry
2,3,4	Number	*Observer's coordinates*: For ground based observatories, the latitude 1) in *degrees*, longitude 2) in *degrees*, and altitude in *m* above see level of the observatory (automatically filled in upon selection of the predefined observatory)
5,6	Epoch	*Time range selection*: Start time 5) and End time 6) for the display
7	Epoch	*Sliding Time selection*: Selected observation configuration within the time range
8	List	*Phase-CML map selection*: A list of Phase-CML maps
9	List	*Satellite selection*: A list of Jovian moon: Io, Europa, Ganymede, Callisto, Amalthea
10	Switch	*Jupiter visibility*: Activate the Jupiter visibility from the observer feature
11	Switch	*Jupiter elevation threshold*: Set the elevation threshold if the "Jupiter visibility" feature is active
12,13	Button	*Time selection*: Move the time range backward 12) or forward 13)
14	Button	*Submit*: Submit the form and update the display panels
15	Display	*Probability map*: The selected Phase-CML map 8) is displayed, with the track of the observation geometry [using the time range 5) to 6)] and the "Jupiter" symbol placed at the time 7). The panel can be used to select the display time by clicking on the observation track. If the "Jupiter visibility" feature is active, the track shows shading depending on the elevation of Jupiter. The reference of the map is given below the figure
16	Cursor	*Observational geometry*: The marker of the selected observational geometry if a "Jupiter" planet symbol
17	Button	*Download map*: The figure can be downloaded as a PDF file
18	Display	*Modeled dynamic spectrum*: A modeled dynamic spectrum, using ExPRES, with a background shading if the "Jupiter visibility" feature is active. A vertical dashed line with markers at the top and bottom is showing the display time
19	Display	*Observation*: If observations are available for the selected observatory, and the selected time range, they are displayed in this panel. Currently, only NDA data can be displayed here

reference frame, with a similar *STATE_VECTOR* query, using the *TIME_AT_TARGET*, and no aberration correction. In the following listing, the `satellite` variable contains the name of the selected moon.

```
1  calc_moon = Calculation(
2      kernels=kernels,
3      api=API,
4      times=date_jupiter,
5      calculation_type="STATE_VECTOR",
6      target=satellite,
7      observer="JUPITER",
8      aberration_correction="NONE",
9      reference_frame="IAU_JUPITER",
10     state_representation="LATITUDINAL",
11     verbose=False
12 )
13 res_moon = calc_moon.run()
14 phase = (180+cml+np.array(res_moon.get("LONGITUDE"))
       )%360
```

Listing 2: Second State Vector query to Webgeocalc: computing the moon's *Phase*.

The Phase of the moon is then:

$$\text{Phase} = (180 + \text{CML} + \text{Long}_{\text{moon}}) \bmod 360 \qquad (2)$$

The elevation of Jupiter for ground observatories is retrieved with a *STATE_VECTOR* call on the *WebGeoCalc* server, using the *RA_DEC* representation. The obtained sky coordinates are transformed into alt-azimuthal coordinates using *astropy* and the observatory location.

5 Summary and perspectives

The Jupiter Probability Tool application is a science ready tool for preparing and analysing Jupiter radio observations. It has already been used in several studies. Louis et al. (2021) prepared a series of joint Jupiter decametric observations on three international LOFAR stations (Ireland, France and Germany) using the Jupiter Probability Tool. Lamy et al. (2022a) is a comment on a published paper. The authors made use of the application to support their argumentation. Lamy et al. (2022b) also made use of the application to confirm that the observed emissions were Io-controlled emissions.

A series of improvement and new features are planned for the next versions of the application. Firstly, new observatories shall be implemented, especially space missions with low frequency radio instrumentation, such as, e.g., Cassini; STEREO-A; STEREO-B; WIND; Galileo; JUICE; Voyager 1; Voyager 2; and Mars Express.

Improvement of the application to adhere to the FAIR (Findable, Accessible, Interoperable, and Reusable) principles (Wilkinson et al., 2016) are also in preparation. One of the planned feature in this context is the addition of provenance (Servillat et al., 2022) information to the output figures (with the provision of the list of citations to be used if the figures are included in a scientific publication), thus improving the reusability of the application products.

Data availability statement

The code of the application is currently not open (except the lines presented in the paper). The data used in this application are all openly available: ExPRES collection (Louis et al., 2020), NDA Jupiter Routine collection (Lamy et al., 2021), Phase-CML maps (Lamy et al., 2022), and the Juno SPICE kernel dataset (Semenov et al., 2017).

Author contributions

BC and LL prepared the application requirements. SA developed the application. BC and LL reviewed and commented the application during the development process. BC wrote the first version of the papier. SA and LL commented and proofread the manuscript.

Funding

Acknowledgments

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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