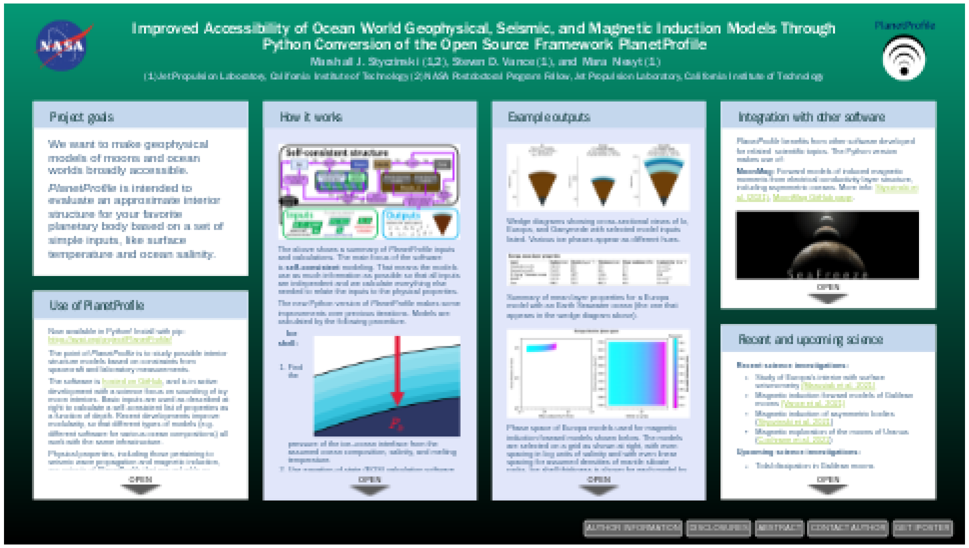
Improved Accessibility of Ocean World Geophysical, Seismic, and Magnetic Induction Models Through Python Conversion of the Open Source Framework PlanetProfile



Marshall J. Styczinski (1,2), Steven D. Vance (1), and Mara Niesyt (1)

(1) Jet Propulsion Laboratory, California Institute of Technology (2) NASA Postdoctoral Program Fellow, Jet Propulsion Laboratory, California Institute of Technology

PlanetProfile

PRESENTED AT:

AbSciCon 2022

PROJECT GOALS

We want to make geophysical models of moons and ocean worlds broadly accessible.

PlanetProfile is intended to evaluate an approximate interior structure for your favorite planetary body based on a set of simple inputs, like surface temperature and ocean salinity.

USE OF PLANETPROFILE

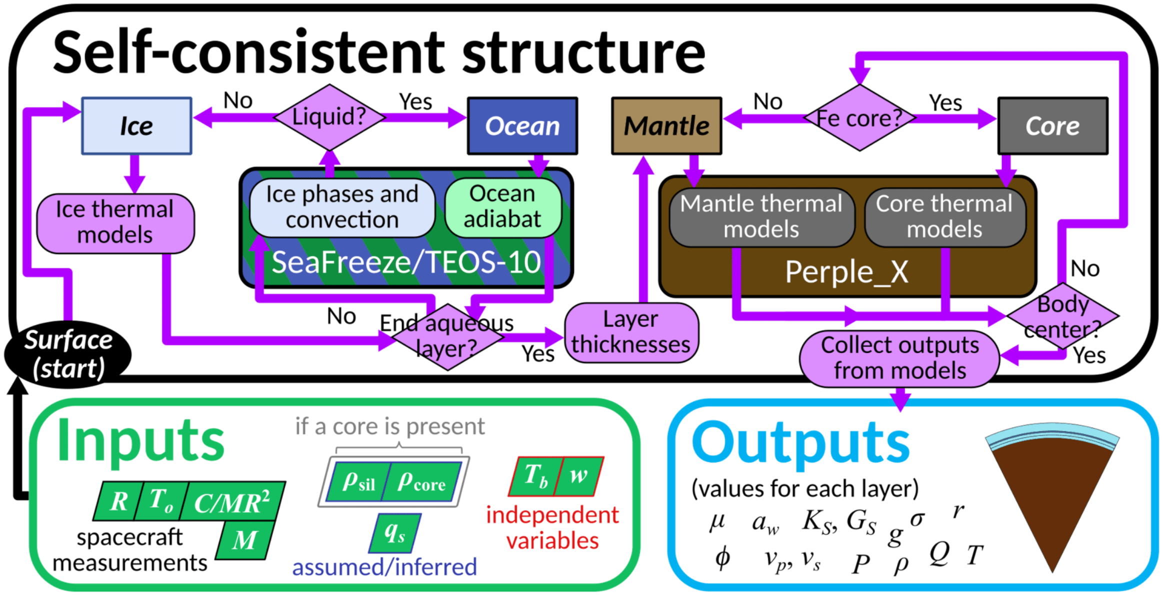
Now available in Python! Install with pip: https://pypi.org/project/PlanetProfile/ (https://pypi.org/project/PlanetProfile/)

The point of *PlanetProfile* is to study possible interior structure models based on constraints from spacecraft and laboratory measurements.

The software is hosted on GitHub (https://github.com/vancesteven/PlanetProfile), and is in active development with a science focus on sounding of icy moon interiors. Basic inputs are used as described at right to calculate a self-consistent list of properties as a function of depth. Recent developments improve modularity, so that different types of models (e.g. different software for various ocean compositions) all work with the same infrastructure.

Physical properties, including those pertaining to seismic wave propagation and magnetic induction, are outputs of *PlanetProfile* that are valuable as forward models. These outputs represent a use of existing constraints from other scientific investigations that can better inform sounding, the determination of properties at depth.

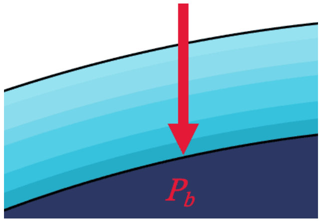
HOW IT WORKS



The above shows a summary of *PlanetProfile* inputs and calculations. The main focus of the software is **self-consistent** modeling. That means the models use as much information as possible so that all inputs are independent and we calculate everything else needed to relate the inputs to the physical properties.

The new Python version of *PlanetProfile* makes some improvements over previous iterations. Models are calculated by the following procedure.

Ice shell:



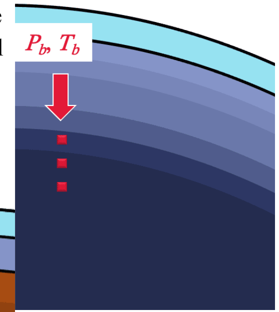
1. Find the pressure of the ice–ocean interface from the assumed ocean composition, salinity, and melting temperature.
2. Use equation-of-state (EOS) calculation software to determine ice properties with depth
3. Determine Rayleigh number and apply convective model for ice shell, if appropriate, and evaluate heat flux through the ice shell.

Ocean:

4. Propagate adiabatic thermal profile downward from the melting P and T at the ice shell until past the expected seafloor, checking for high-pressure ices at each step

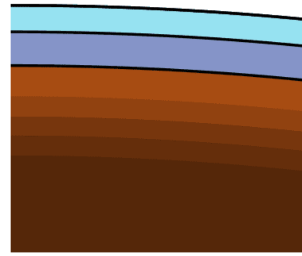
Silicates:

5. For waterless bodies, we start here with an assumed heat flux. For ocean worlds, use each hydrosphere layer as a starting "guess" size for many mantles to consider. In all cases, propagate a conductive thermal profile to the center of the body. Only keep profiles with a mass consistent with the known total mass. Use EOS software for physical properties at each step.



Iron core:

6. When present, propagate an adiabatic thermal profile starting from each silicate layer that will keep the total body mass consistent. Use EOS software for physical properties at each step.



7. Calculate the moment of inertia for each mass-matching profile and select the one closest to the measured value.
8. Calculate seismic properties and electrical properties for all layers.

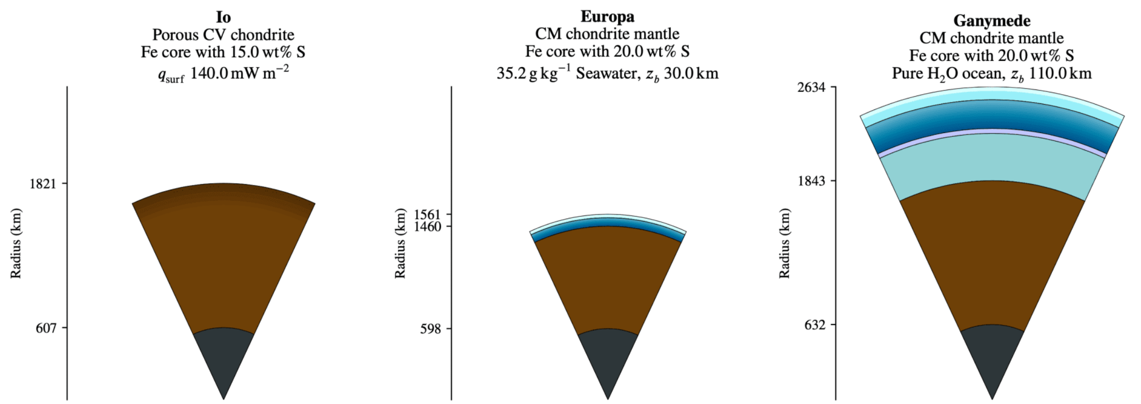
PlanetProfile uses the following as inputs for each model:

- Total mass M
- Radius R
- Surface temperature T_{surf}
- Surface pressure P_{surf}
- Axial moment of inertia C/MR^2

and the following as variable assumptions for each model:

- Dissolved solute composition in ocean
- Ocean salinity w
- Ice bottom (ocean melting) temperature T_b
- Silicate composition
- Core composition (if present)
- Rock and ice porosity functions $\phi(P)$

EXAMPLE OUTPUTS

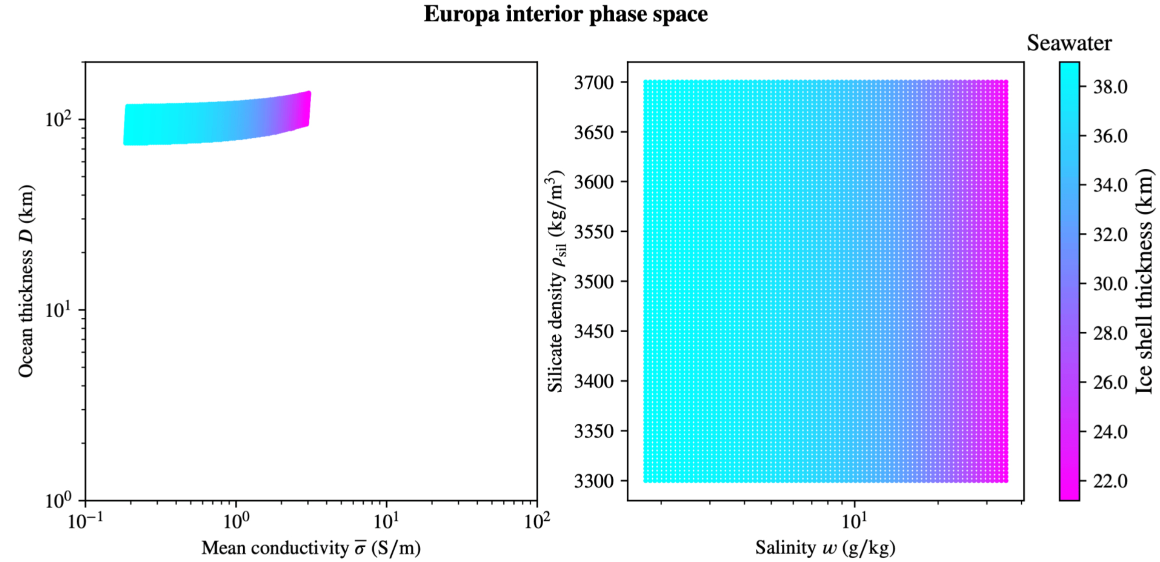


Wedge diagrams showing cross-sectional views of Io, Europa, and Ganymede with selected model inputs listed. Various ice phases appear as different hues.

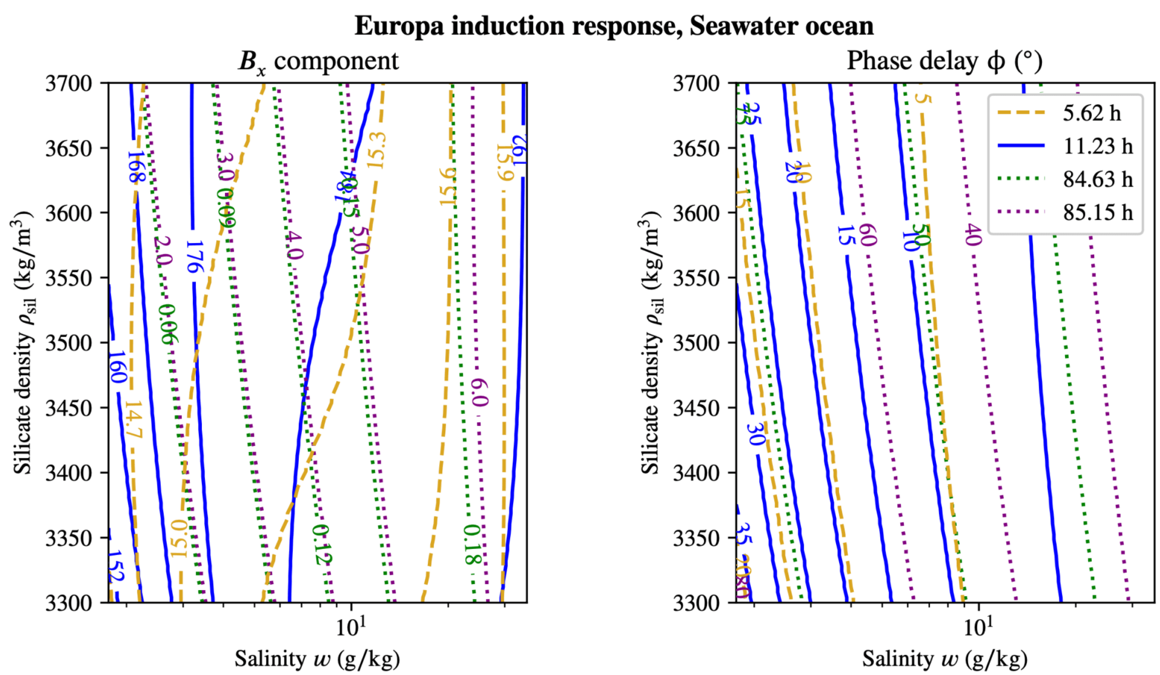
Europa mean layer properties

Layer	**Radius** (km)	**Density** (kg m^{-3})	**Thickness** (km)	**Shear modulus** (GPa)	**Conductivity** (S m^{-1})
Conductive ice Ih	1561.0	929	19.5	3.8	1.0×10^{-8}
Convective ice Ih	1541.5	922	10.4	3.5	1.0×10^{-8}
35.2 g kg^{-1} Seawater ocean	1531.0	1066	70.9	0.0	2.84
Mantle	1460.1	3289	861.4	33.2	1.0×10^{-16}
Core	598.6	5653	598.6	30.2	1.0×10^{6}

Summary of mean layer properties for a Europa model with an Earth Seawater ocean (the one that appears in the wedge diagram above).



Phase space of Europa models used for magnetic induction forward models shown below. The models are selected on a grid as shown at right, with even spacing in log units of salinity and with even linear spacing for assumed densities of mantle silicate rocks. Ice shell thickness is shown for each model by color, and mean ocean layer thickness and conductivity are shown at left.

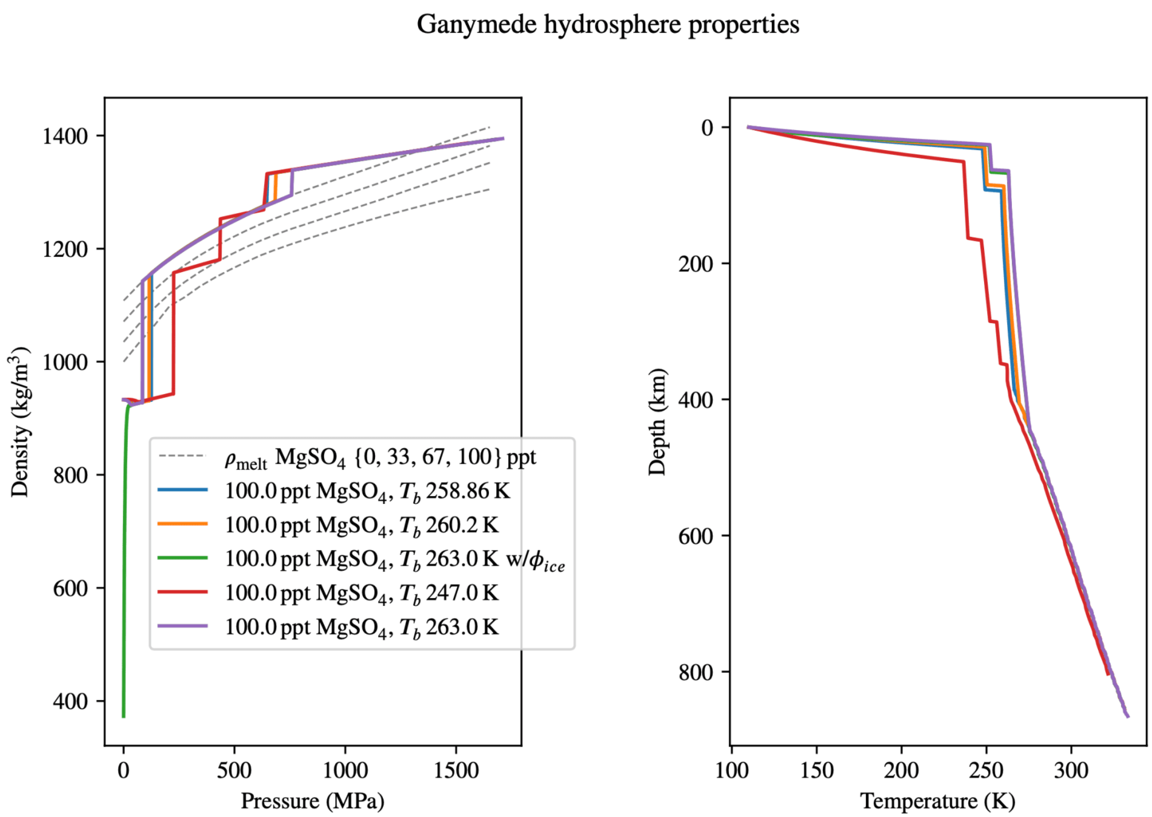


Induced magnetic field plot for Europa models in the phase space plot above. The 4 strongest magnetic oscillations applied by Jupiter are shown. Contours show the strength of the induced magnetic field at the surface for each salinity/silicate density combination.

Ganymede model comparisons

$MgSO_4$ 100.0 $g\,kg^{-1}$	M (kg)	1.4819×10^{23}	1.4819×10^{23}	1.4819×10^{23}	1.4819×10^{23}	1.4819×10^{23}
	M_{model} (kg)	1.4815×10^{23}	1.4814×10^{23}	1.4808×10^{23}	1.4811×10^{23}	1.4810×10^{23}
	C/MR^2	0.31150 ± 0.00280	0.31150 ± 0.00280	0.31150 ± 0.00280	0.31150 ± 0.00280	0.31150 ± 0.00280
	C_{model}/MR^2	$0.31151^{+0.00022}_{-0.00022}$	$0.31149^{+0.00022}_{-0.00021}$	$0.31145^{+0.00022}_{-0.00021}$	$0.31129^{+0.00096}_{-0.00092}$	$0.31140^{+0.00021}_{-0.00020}$
	$\rho_{rock,mean}$ ($kg\,m^{-3}$)	3291	3291	3290	3287	3290
	T_b (K)	258.86	260.2	263.0	247.0	263.0
	q_{surf} ($mW\,m^{-2}$)	11.3	12.2	13.8	4.6	14.0
	q_{con} ($mW\,m^{-2}$)	12.2	13.1	14.5	6.1	14.7
	η_{con} (Pa s)	4.99×10^{14}	4.28×10^{14}	3.90×10^{14}	1.21×10^{15}	3.90×10^{14}
	D_{Ih} (km)	93.7	86.3	67.5	166.2	64.1
	D_{III} (km)	-	-	-	120.2	-
	$D_{V,under}$ (km)	-	-	-	62.8	-
	D_{ocean} (km)	288.6	314.5	370.4	7.8	371.7
	D_{V} (km)	-	-	-	38.5	-
	D_{VI} (km)	471.4	455.5	416.2	414.0	431.4
	$\overline{\sigma}_{ocean}$ ($S\,m^{-1}$)	2.2	2.4	2.9	2.1	2.9
	R_{surf} (km)	2634.1	2634.1	2634.1	2634.1	2634.1
	R_{rock} (km)	1780.4	1777.8	1779.9	1824.7	1767.0
	R_{core} (km)	617.2	622.2	617.0	541.3	642.0
	ϕ_{ice}	-	-	0.60	-	-
	ϕ_{rock}	-	-	-	0.60	-

Table comparing model outputs for 5 Ganymede models, all with 100 g/kg $MgSO_4$(aq) oceans. Also listed are 4 critical inputs: the body mass M, axial moment of inertia C/MR^2, ocean melting temperature T_b, and body radius R_{surf}. Each model differs in assumed T_b and whether porosity is modeled in rocks, ice, or neither.



Density vs. pressure and temperature vs. depth for the same 5 Ganymede models listed in the table above, along with melting curves for 4 reference salinities. High-pressure ice phases appear as upward jumps in the density curves. In one model where porosity in ice is modeled (green), porous ice near the surface shows a markedly lower density.

INTEGRATION WITH OTHER SOFTWARE

PlanetProfile benefits from other software developed for related scientific topics. The Python version makes use of:

MoonMag: Forward models of induced magnetic moments from electrical conductivity layer structure, including asymmetric oceans. More info: Styczinski et al. (2021) (https://doi.org/10.1016/j.icarus.2021.114840), MoonMag GitHub page (https://github.com/itsmoosh/MoonMag).

MoonMag

SeaFreeze: Determines equation-of-state (EOS) properties of liquid and solid water, including ice phase, as a function of pressure and temperature. Currently only covers pure H_2O, but is intended to cover several dissolved salts and mixtures in the coming months. More info: Journaux et al. (2020) (https://doi.org/10.1029/2019JE006176), SeaFreeze GitHub page (https://github.com/Bjournaux/SeaFreeze).

Gibbs Seawater (GSW) toolbox of TEOS-10: Calculates EOS properties of Seawater over a range of Earth-relevant conditions of temperature, pressure, and salinity. This range is relevant to moons the size of Europa and smaller. More info: TEOS-10 website (http://www.teos-10.org/), GSW-Python GitHub page (https://github.com/TEOS-10/GSW-Python).

Perple_X: Determines thermodynamic (EOS) properties of elemental mixtures at conditions relevant to silicate mantles and possible metallic cores. More info: Perple_X website (https://www.perplex.ethz.ch/).

RECENT AND UPCOMING SCIENCE

PlanetProfile is a versatile tool for scientific study of large moon and ocean world interior properties.

Recent science investigations:

- Study of Europa's interior with surface seismometry (Marusiak et al. in press) (https://doi.org/10.1002/essoar.10509557.1)
- Magnetic induction forward models of Galilean moons (Vance et al. 2021) (https://doi.org/10.1029/2020JE006418)
- Magnetic induction of asymmetric bodies (Styczinski et al. 2021) (https://doi.org/10.1016/j.icarus.2021.114840)
- Magnetic exploration of the moons of Uranus (Cochrane et al. 2021) (https://doi.org/10.1029/2021JE006956)

In-progress science investigations:

- Seismic modeling of Titan with surface clathrates (Bryant et al., LPSC 2022) (https://www.hou.usra.edu/meetings/lpsc2022/pdf/1542.pdf)
- Tidal dissipation in Galilean moons (Vance et al., this meeting) (https://agu.confex.com/agu/abscicon21/meetingapp.cgi/Paper/1029720)
- Characteristics of Europa's possible iron core
- Magnetic induction investigations of several moons of Jupiter, Saturn, and Uranus

Future developments:

- Graphical user interface (GUI)
- Tutorials and lesson plans for geophysics
- Mantle convection
- Self-consistent tidal heating
- More flexibility in ocean solute composition
- Alignment between Matlab and Python (Python has more features now)

DISCLOSURES

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AUTHOR INFORMATION

Marshall J. Styczinski[1,2], Steven D. Vance[1], and Mara Niesyt[1]

ABSTRACT

Computational software for planetary science and astrobiology is vital for understanding how complex systems interact, and for the analysis of sparse spacecraft data. *PlanetProfile* is an open source framework for modeling the interior of planetary bodies, especially ocean worlds, and is available in Matlab. We have rebuilt *PlanetProfile* in Python to improve its accessibility, as Python is free and widely used in scientific computing. *PlanetProfile* features such as the calculation of induced magnetic fields and seismic properties permit wider availability of these important tools for research purposes. An upcoming release of *PlanetProfile* contains the converted and streamlined software. New features such as a graphical user interface are in development that will support new users in taking advantage of these valuable tools.