IGRF in Python

Community consensus & tools for near-Earth geomagnetic field models

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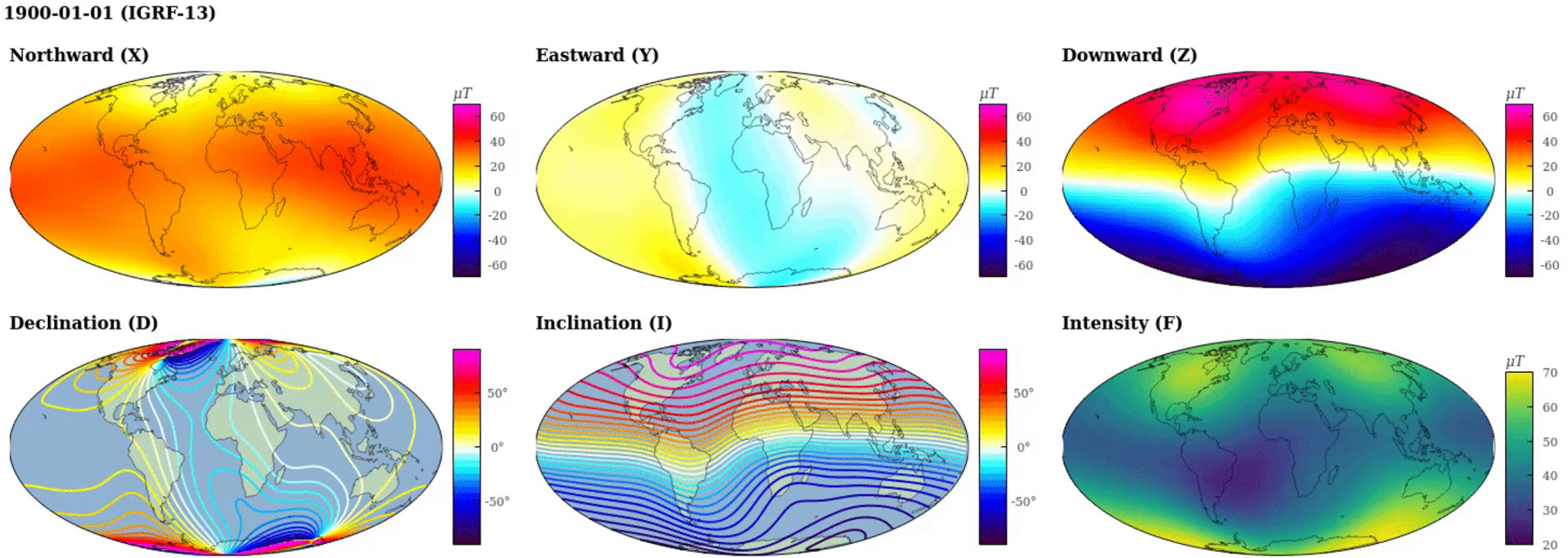
Outline

- IGRF is used for many different purposes
- Need a simple reference Python implementation of IGRF, agreed by community
- Could coordinate efforts better
- More generally:
  A pattern to follow for other models?
  e.g. IRI, MSIS-E, ...
  (considering sustainability, wide user base, ...)

...

What is IGRF?

International Geomagnetic Reference Field 13 defined over 1900-



What is IGRF?

$$\vec{B} = -\nabla V$$

$$V = R_E \sum_{l=1}^{N} \sum_{m=0}^{l} \left(g_l^m \cos m\phi + h_l^m \sin m\phi \right) \left(\frac{R_E}{r} \right)^{l+1} P_l^m(\cos\theta)$$

Spherical harmonic description up to degree l=13 (195 Gauss coefficients)

Snapshot every 5 years with linear interpolation between

```
# 13th Generation International Geomagnetic Reference Field Schmidt semi-normalised sphe
# in units nanoTesla for IGRF and definitive DGRF main-field models (degree n=1,8 nanoTe
c/s deg ord IGRF IGRF   IGRF   IGRF   IGRF   IGRF   IGRF   IGRF   IGRF   DGRF   DGRF   D
g/h n m 1900.0 1905.0 1910.0 1915.0 1920.0 1925.0 1930.0 1935.0 1940.0 1945.0 1950.0 195
g  1  0 -31543 -31464 -31354 -31212 -31060 -30926 -30805 -30715 -30654 -30594 -30554 -30
g  1  1  -2298  -2298  -2297  -2306  -2317  -2318  -2316  -2306  -2292  -2285  -2250  -2
h  1  1   5922   5909   5898   5875   5845   5817   5808   5812   5821   5810   5815   5
g  2  0   -677   -728   -769   -802   -839   -893   -951  -1018  -1106  -1244  -1341  -1
g  2  1   2905   2928   2948   2956   2959   2969   2980   2984   2981   2990   2998   3
h  2  1  -1061  -1086  -1128  -1191  -1259  -1334  -1424  -1520  -1614  -1702  -1810  -1
g  2  2    924   1041   1176   1309   1407   1471   1517   1550   1566   1578   1576   1
h  2  2   1121   1065   1000    917    823    728    644    586    528    477    381
g  3  0   1022   1037   1058   1084   1111   1140   1172   1206   1240   1282   1297   1
g  3  1  -1469  -1494  -1524  -1559  -1600  -1645  -1692  -1740  -1790  -1834  -1889  -1
```

What is IGRF?

- Construction of IGRF is a 5-yearly activity organised by IAGA
- Many more complex candidate models are merged (weighted average of Gauss coefficients): this is published as the IGRF
  https://www.ngdc.noaa.gov/IAGA/vmod/index.html
  International Geomagnetic Reference Field: the thirteenth generation, Alken et al. 2021

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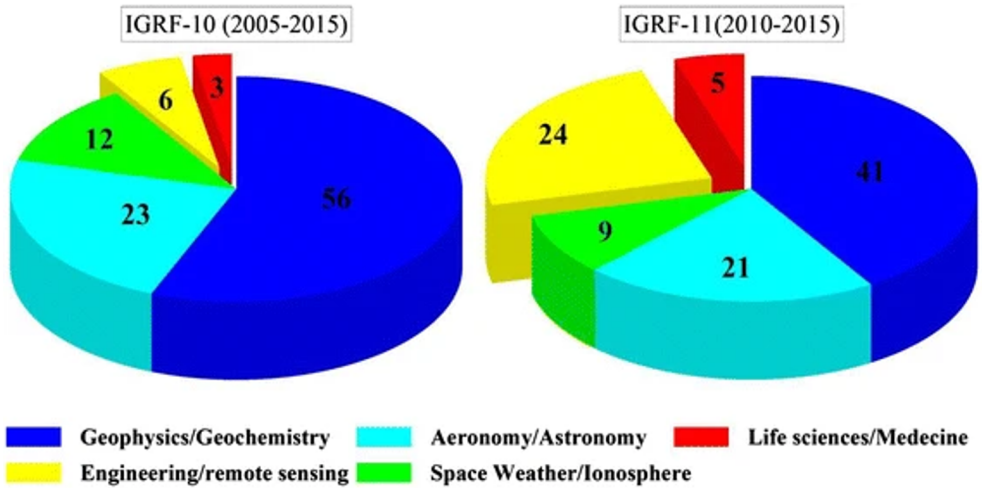
```

Beyond IGRF

- When is IGRF not enough?
  e.g. probing ionospheric magnetic signals at LEO -> better to use more accurate internal field and magnetospheric model like CHAOS
  See magneticearth.org/pages/models.html
- Need a smoother pathway for people to understand when to move beyond IGRF, and how to do that

Wide & Varied User Base

- Data analysis/interpretation
- Numerical modelers
- Operational users - NASA, NOAA, DoD, Commercial Entities
- Students



Uses in space physics

- Model evaluation (what is the main field at x,y,z?)
- Field line tracing
- Coordinate systems (e.g. AACGM, QD …)
- Coupling to Tsyganenko models
- Interpreting magnetometer data
- Input into first-principal/empirical models
- ...

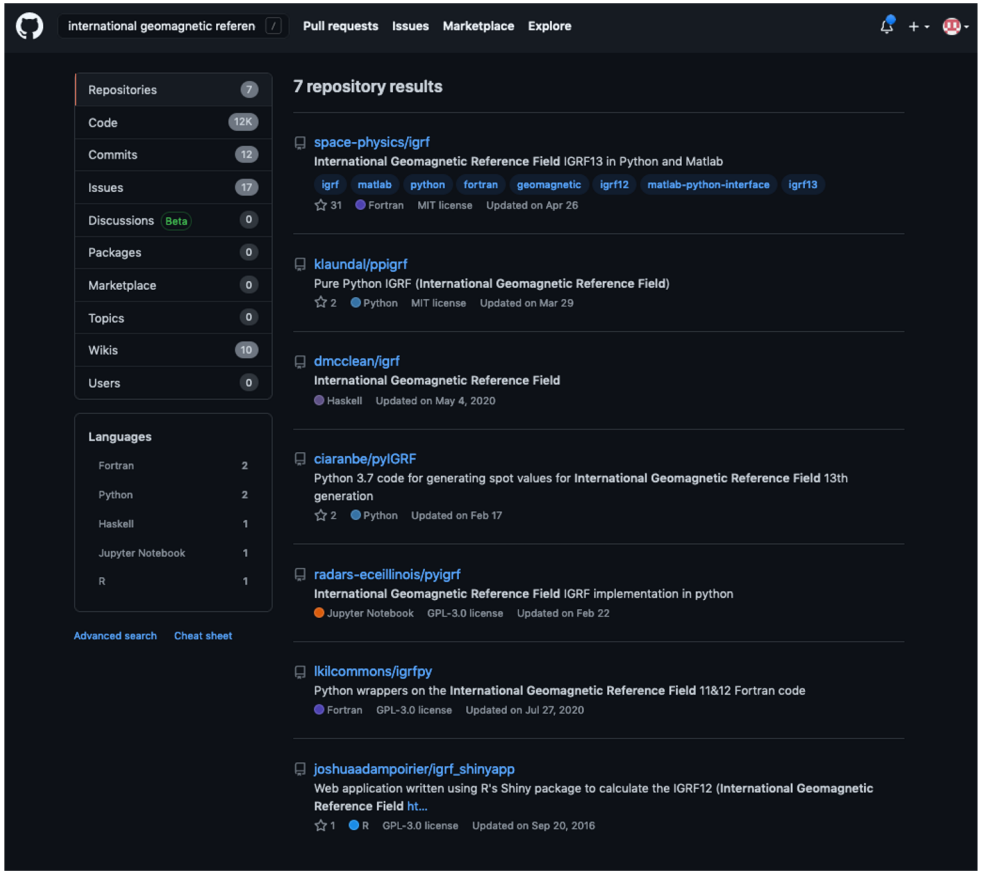
Uses in geophysics

- Model evaluation (what is the main field at x,y,z?)
- Geomagnetic field modelling (power spectra, model comparison...)
- Correction processes in crustal and MT surveys
- ...

Thébault, E., Finlay, C. & Toh, H. Special issue “International Geomagnetic Reference Field—the twelfth generation”. *Earth Planet Sp* **67,** 158 (2015). https://doi.org/10.1186/s40623-015-0313-0

Many Existing Implementations

- IAGA traditionally publish an old Fortran code updated with the latest coefficients
- Many other implementations and web services exist
- IGRF coefficients are also used in other tools (e.g. AACGM, GEOPACK)
- Currently not an obvious choice which Python package to use
  - “International Geomagnetic Reference Field” - 7 repos
  - “IGRF” - 45 repos



Tabulation of various packages: https://github.com/ciaranbe/pyIGRF/issues/2

Potential Requirements

- Ease of use
  - Simple pip install that works on all platforms immediately
  - Simple interface
- Performance
  - A pure Python implementation (using available tools in numpy/scipy) is slower
  - eoxmagmod from Swarm mission (C++ underneath) is fastest - WIP to fix distribution & documentation (provides several models beyond IGRF)
- Features
  - Flexible forwards evaluation
  - Field line tracing (see e.g. rstoneback/OMMBV)
  - Geomagnetic field modelling toolbox (much already available in ChaosMagPy)
  - Select which version (year) of the model to use
- Maintainability
  - Clean code base
  - Well documented, both for users and developers
  - Avoid “scope creep” (adding many specialized features such that the package becomes large and/or fragile)
  - A guiding/parent organization to support development

Discussion Questions

- Is having many “python IGRFs” a problem?
- Can we as a community coordinate our efforts better?
- Who should be in charge of the “standard” python IGRF library?
- What features should the “standard” library have?
- How should this effort be organized/funded?
- How can this apply to other similar tools (IRI, MSIS, ect)?

Discussion Notes

- NGDC python package
- CCMC provides access
- Nice if IAGA is involved - not strictly required
- CCMC web interface - nice resource for the community, but many people want to be able run the model locally
- Coordinate - solar community has gathered around sunpy, astropy, ect?
  - Do we want to try to take this approach? Organize the community around a single packages
- Centralized package - dependencies issues
  - Can be problem for maintenance
  - Maybe all these large models can be collected at least
- NASA ML call - produce something ML ready (machine learning)
  - Maybe helpful to have a funding opportunity like this
  - HDEE - possible funding opportunity - 1-2 years
  - White paper for decadal survey
  - Opportunity for our community to demonstrate the advantages of open source
- Pysat - lets community be decentralized, but pysat connects everything - Metapackage?
  - Let things easily talk to each other
- Software publication is important!!!
  - Publishing jupyter notebooks
  - JOSS