# Grid4Earth: An Open-Source Python Ecosystem for Geospatial Data Integration Using an Ellipsoidal HEALPix DGGS

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**Abstract**

The rapid growth in Earth observation (EO) and Digital Twin Earth data volumes creates a need for global, reproducible, and cloud-native spatial representations. Conventional latitude–longitude grids and projected tiling systems remain useful, but they introduce projection boundaries, non-uniform cell areas, and repeated reprojection costs when combining multi-source products. Grid4Earth addresses this problem through an open-source Python ecosystem built around an ellipsoidal HEALPix Discrete Global Grid System (DGGS) representation and Zarr-based data handling. The ecosystem consists of four composable packages: `healpix-geo` for WGS84-aware indexing and coverage queries, `healpix-resample` for CPU/GPU-capable regridding, `healpix-plot` for visualisation, and `healpix-analyse` for diagnostics and analysis. We situate Grid4Earth in relation to previous DGGS comparisons, XDGGS, and OGC API – DGGS work, focusing on the implementation layer required for EO workflows. When WGS84 geodetic latitude is passed directly to spherical HEALPix, local cell areas vary by up to approximately 0.9% because of Earth's non-spherical shape. Grid4Earth preserves the HEALPix equal-area property on WGS84 through an authalic-latitude mapping. The ecosystem has been exercised in HEALPix/Zarr workflows for Sentinel-2, Sentinel-3, ERA5, CAMS, and DestinE Climate Digital Twin outputs. This paper describes the ellipsoidal geometry, the CPU/GPU-capable resampling architecture, and the implementation of metadata fields defined by CF 1.13 and version 1 of the Pilot Zarr DGGS convention, establishing ellipsoidal HEALPix/Zarr as a common representation that connects climate and Digital Twin Earth datasets with ellipsoidal EO datasets.

## 1. Introduction

Earth observation (EO) data volumes continue to grow through Copernicus Sentinel missions, climate reanalysis, and Digital Twin Earth initiatives. These data are commonly distributed as projected raster tiles, swath products, or model grids. Such representations are mature and well supported, but they create difficulties for global analysis: latitude–longitude grids have latitude-dependent cell areas; UTM and polar products introduce zone boundaries; and cross-sensor or EO–model workflows require repeated reprojections and interpolations. The Sentinel-2 UTM tiling system, for example, has been shown to include substantial spatial overhead due to overlapping tiles (Bauer-Marschallinger and Falkner, 2023).

Discrete Global Grid Systems (DGGS) offer an alternative by assigning observations to globally defined hierarchical cells with unique identifiers (Open Geospatial Consortium, 2021; Purss et al., 2019). Among DGGS families, HEALPix is attractive for EO and climate workflows because it provides equal-area cells, an iso-latitude structure, aperture-4 refinement, and mature software for spherical analysis (Górski et al., 2005; Zonca et al., 2019). HEALPix is already used beyond astronomy; notably, the Destination Earth Climate Change Adaptation Digital Twin uses HEALPix as a common output grid, while the 2025 WCRP Global Kilometre-Scale Hackathon used a hierarchy of common HEALPix grids to enable multi-model analysis (Doblas-Reyes et al., 2026; Gettelman et al., 2026). However, classical HEALPix is defined on the sphere, while EO data, by contrast, are geodetically referenced to an ellipsoid such as World Geodetic System 1984 (WGS84). This creates both an opportunity and an implementation gap: HEALPix can provide a common global data cube index, but practical EO workflows need ellipsoid-aware indexing, regridding, metadata, and cloud-native storage.

The Grid4Earth project, funded by the ESA Digital Twin Earth framework, develops this missing implementation layer. Its goal is to provide reusable, free, and open-source software for converting, storing, visualising, and analysing EO and Digital Twin data using an ellipsoidal HEALPix/Zarr representation. The paper makes four contributions. First, it presents the Grid4Earth Python ecosystem and the role of each package. Second, it describes the workflow from geolocated EO products to HEALPix/Zarr data cubes. Third, it reports representative implementation checks and use cases. Fourth, it documents the implementation of metadata fields defined by the Climate and Forecast (CF) Conventions 1.13 (CF Community, 2025) and the Pilot Zarr DGGS convention (Zarr-conventions contributors, 2026), together with alignment with Earth Observation Processing Framework (EOPF) structures (European Space Agency, 2026) and OGC DGGS activities (Open Geospatial Consortium, 2025).

| Package | Purpose | Principal capabilities |
|---|---|---|
| `healpix-geo` | Geospatial indexing layer | WGS84-aware HEALPix cell assignment, lon/lat to cell-id conversion, NESTED/RING/zuniq handling, coverage queries for boxes, cones and polygons, and metadata support for ellipsoidal interpretation (GRID4EARTH contributors, 2026c). |
| `healpix-resample` | Regridding layer | Sparse mappings from geodetic source coordinates to target HEALPix cells, with nearest-neighbour and Point Spread Function (PSF)/multi-point weighted strategies; CPU and GPU execution through PyTorch (GRID4EARTH contributors, 2026e). |
| `healpix-plot` | Visualisation layer | Quick static maps of HEALPix cell data by rasterising values to a regular lon/lat sampling grid and rendering with Matplotlib/Cartopy, with ellipsoidal coordinate operations from `healpix-geo` (GRID4EARTH contributors, 2026d). |
| `healpix-analyse` | Analysis layer | PyTorch-based spherical-harmonic analysis, power spectra, gauge-equivariant convolution, and multi-resolution operators, applicable to both native spherical climate-model fields and authalic-mapped ellipsoidal EO fields on a common grid (GRID4EARTH contributors, 2026b). |

Table 1. Main Grid4Earth packages and their roles in the ellipsoidal HEALPix/Zarr workflow.

## 2. Background and Related Work

DGGS have been proposed as a foundation for global data cubes because they provide hierarchical, globally consistent spatial units and cell identifiers (Sahr et al., 2003; Purss et al., 2019). Existing open-source implementations include H3, S2, rHEALPix, DGGRID, ISEA variants, and HEALPix. These systems optimise different properties: H3 and S2 are mature spatial indexing systems; hexagonal grids such as ISEA variants offer attractive neighbourhood relations; rHEALPix provides an ellipsoidal equal-area DGGS based on a rearranged HEALPix projection; and HEALPix provides equal-area iso-latitude cells and spherical harmonic compatibility (Gibb et al., 2016; Uber Technologies, 2019; Veach et al., 2017; Górski et al., 2005).

Rather than repeating broad comparisons of DGGS geometries and open-source software, we focus on the implementation required for EO workflows. Previous studies have compared area and shape distortions in open-source DGGS implementations (Kmoch et al., 2022), while the XDGGS work introduced a community-developed Xarray extension for DGGS-indexed planetary data cube computations (Kmoch et al., 2024). XDGGS integrates DGGS cell identifiers into the Xarray data model and provides a high-level API for selection, alignment, and data cube operations. It also updated HEALPix equal-area and compactness assessments and positioned DGGS as a practical abstraction for Pangeo-style workflows.

A complementary line of work concerns cloud-native access. Kmoch et al. (2026) describe an architecture that combines DGGS, Zarr, Parquet, and OGC API DGGS for cloud-native digital twins. In that architecture, DGGS-indexed Zarr archives can be accessed directly by Xarray/Dask for high-performance workflows, while OGC API DGGS exposes the same data to lightweight web clients. Grid4Earth builds on this architectural context but focuses on the EO implementation layer: ellipsoidal HEALPix indexing, resampling to HEALPix cells, HEALPix-specific plotting, and diagnostic tools.

Against this background, the present paper focuses on the implemented open-source ecosystem, specifically the reusable `healpix-geo`, `healpix-resample`, `healpix-plot`, and `healpix-analyse` components, its workflow architecture, the equal-area interpretation of HEALPix on the WGS84 ellipsoid through authalic-latitude mapping, and the implementation of relevant metadata fields defined by CF 1.13 and version 1 of the Pilot Zarr DGGS convention. It reports numerical consistency checks for the authalic transformation and representative functional checks across EO and climate product types.

## 3. Grid4Earth Software Ecosystem

Grid4Earth's reusable output is a set of four general-purpose packages (Table 1), rather than a collection of separate mission-specific converters. A separately developed converter package orchestrates these components through product-specific configurations, while the plotting and analysis packages support functional checks and downstream use. Users can therefore adopt only the layers needed for a workflow or install the complete stack. Table 1 summarises the current roles of the packages.

To simplify adoption, a project-level meta-package registry is also provided. The current registry distributes curated requirements files and environment specifications for a consistent installation of Grid4Earth packages (GRID4EARTH contributors, 2026a). In tutorials, this can be presented as a single-stack installation pathway, while advanced users can install individual packages separately.

## 4. Workflow and Implementation Architecture

The Grid4Earth workflow converts geolocated EO or model data into ellipsoidal HEALPix/Zarr data cubes. In its generic form, it opens input products lazily with Xarray. The workflow is designed to support Sentinel-2 MSI L1C/L2A, Sentinel-3 OLCI/SLSTR, DestinE Climate Digital Twin outputs, auxiliary data such as DEMs, ERA5/CAMS Gaussian-grid outputs, and generic longitude/latitude grids or point clouds. Table 2 distinguishes implemented workflows from target use cases.

A Grid4Earth converter package has been exercised with Sentinel-2 MSI L1C/L2A, Sentinel-3 OLCI/SLSTR, ERA5/CAMS Gaussian-grid outputs, and DestinE Climate Digital Twin outputs. This functional coverage spans tiled rasters, geolocated swaths, Gaussian grids, and spherical HEALPix model outputs; it should not be interpreted as a quantitative product-scale validation. Figure 1 summarises the generic data flow.

The first geospatial step is the extraction and verification of the coordinates. The source longitude and latitude may come from geolocation arrays, tie-points, or projection metadata. A target

| Input class | Native geometry | Implementation status and role in the Grid4Earth workflow |
|---|---|---|
| Sentinel-2 MSI L1C/L2A | UTM tiled products with 10 m, 20 m and 60 m groups | Converted to HEALPix/Zarr groups with the Grid4Earth converter package across L1C and L2A products. |
| Sentinel-3 OLCI/SLSTR | Geolocated swath or sensor grids with several resolutions | Irregular EO samples assigned to target HEALPix cells with the Grid4Earth converter package, representing multi-instrument products in a common DGGS/Zarr structure. |
| Destination Earth Climate Change Adaptation Digital Twin | Native model grids internally; delivered as spherical HEALPix in GRIB format | Converted from spherical HEALPix/GRIB to ellipsoidal HEALPix/Zarr with the Grid4Earth converter package; illustrates the explicit metadata needed to distinguish spherical and ellipsoidal HEALPix interpretations when co-locating climate and EO data. |
| Auxiliary data and DEMs | Geographic, projected or mission-specific grids | Target use case for common cell-level support of orthorectification, masks, terrain variables and reference layers. |
| ERA5/CAMS Gaussian-grid outputs | Regular Gaussian reduced grids at model resolution | Converted with the Grid4Earth converter package; supports co-locating reanalysis and forecast fields with EO products on a common HEALPix/Zarr grid. |
| Generic lon/lat samples | Points, swaths or rectilinear grids | Implemented in `healpix-resample` and documented through reusable examples for point clouds and generic longitude/latitude samples outside mission-specific configurations (GRID4EARTH contributors, 2026e). |

Table 2. Representative input classes considered by Grid4Earth conversion workflows.

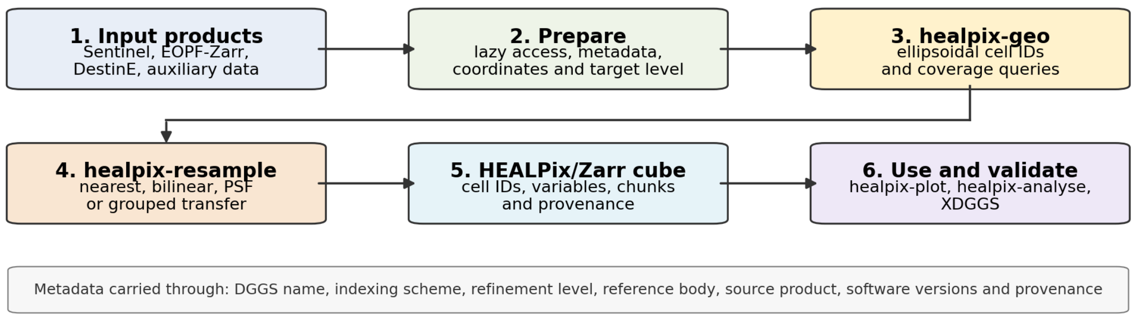


Figure 1. Grid4Earth workflow from geolocated EO or climate products to ellipsoidal HEALPix/Zarr data cubes.

HEALPix refinement level is selected from the resolution of the native product and the intended use. `healpix-geo` then assigns each source coordinate to a HEALPix cell identifier under the selected indexing scheme and reference body. Coverage queries are used to derive the target cell set for a region of interest, for example, from a bounding box, cone, or polygon. This step can reduce the conversion domain before values are resampled and also provides an independent check that the output footprint matches the expected product extent.

The second step is the transfer of values. `healpix-resample` constructs a sparse mapping from source samples to target cells and applies it to variables. For multi-band products, the mapping can be reused for several bands. The current public implementation provides nearest-neighbour and PSF/multi-point weighted mappings. Product-specific workflows may subsequently aggregate multiple source samples assigned to the same target cell.

The output is a HEALPix-indexed Zarr store. The spatial coordinate is represented by cell identifiers, typically in NESTED order because it preserves hierarchy and spatial locality. Variables are stored along dimensions such as cell, time, band and refinement level. Multi-resolution products can be represented as Zarr groups, each carrying its own refinement-level metadata. Grid4Earth output records the DGGS name, indexing scheme, refinement level, coordinate variable, and ellipsoid or reference body. Product-specific metadata also describe source product identifiers, regridding methods, software versions, chunking, compression, and provenance.

This design separates reusable software from product-specific configuration. A Grid4Earth converter package orchestrates the public packages through settings for Sentinel, EOPF-compatible, and model products rather than maintaining a separate converter for each product family. The converter is currently being prepared for public release. Researchers can invoke the public packages directly in notebooks, while operational teams can run the same functions in containerised or cloud workflows.

## 5. Implementation Status and Representative Use Cases

This section reports representative functional and numerical consistency checks of the current implementation. Product-scale quantitative benchmarks of resampling accuracy, runtime, memory use, storage efficiency, and cloud-access performance are outside the scope of this paper and will be reported separately. Table 3 summarises the checks discussed here.

### 5.1 Authalic interpretation and numerical consistency

Classical HEALPix is spherical. Passing geodetic latitude directly to spherical HEALPix is simple but not area-preserving on an ellipsoid such as WGS84. For WGS84, this direct interpretation produces a maximum relative cell-area distortion of approximately 0.9% (Figure 2, orange curve). Grid4Earth instead converts geodetic latitude $\phi$ to authalic latitude $\xi$, while leaving longitude unchanged, before assigning HEALPix indices. For an ellipsoid with eccentricity $e$, the transformation is (Karney, 2024)

$$\begin{aligned} q(\phi) &= \frac{(1-e^2)\sin\phi}{1-e^2\sin^2\phi} \\ &\quad - \frac{1-e^2}{2e}\ln\left(\frac{1-e\sin\phi}{1+e\sin\phi}\right), \\ \sin\xi &= \frac{q(\phi)}{q(\pi/2)}. \end{aligned} \tag{1}$$

The inverse transformation returns geodetic latitude and is evaluated using the numerically stable auxiliary-latitude formulation described by Karney (2024). The equal-area interpretation follows analytically from the authalic-latitude construction (Figure 3), while implementation tests verify numerical consistency of the forward and inverse transformations. Expressed as an equivalent meridional distance, the round-trip latitude error remains below 1 nanometre over the full latitude range.

Standard spherical harmonic transforms can be applied to fields expressed in authalic coordinates using the authalic-sphere area measure. Because climate and Digital Twin Earth outputs are natively spherical while EO products are authalic-mapped from WGS84, `healpix-analyse` allows both to be analysed with the same spectral toolchain once expressed on the authalic sphere – a direct route for co-analysing climate and EO fields on a common grid. To quantify the positional effect of the ellipsoidal interpretation, we compared the locations assigned to identical HEALPix cell indices under the spherical and WGS84 conventions, as illustrated in Figure 4. The resulting meridional displacement is zero at the equator, increases to a maximum of approximately 14.2 km near $\pm 45°$ latitude, and decreases again towards the poles. This displacement is a property of the latitude mapping and is essentially independent of the HEALPix refinement level; level 8 is used here only to sample cell centres.

### 5.2 Converter execution and resampling checks

To assess component integration and deployment, the Grid4Earth converter package was executed end to end in a containerised cloud environment using a Sentinel-2 L1C product in EOPF Zarr format. The product was converted to ellipsoidal HEALPix/Zarr with refinement level 20 for the source 10 m bands, level 19 for the source 20 m bands, and level 17 for the source 60 m bands.

Beyond this Sentinel-2 L1C example, the converter has also been exercised with the other implemented EO and climate product classes listed in Table 2, producing ellipsoidal HEALPix/Zarr stores.

Nearest-neighbour and PSF/multi-point weighted mappings have been exercised with synthetic longitude/latitude point clouds at several HEALPix refinement levels on both CPU and CUDA-enabled GPU.

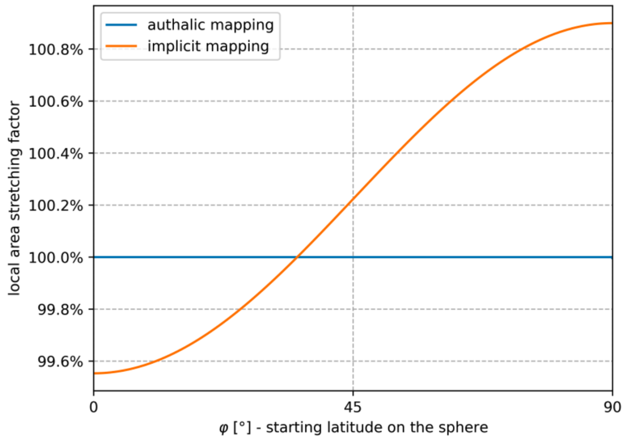


Figure 2. Latitude dependence of local areal scale distortion on the WGS84 ellipsoid for a direct geodetic-latitude interpretation ("implicit", orange curve) and an authalic-latitude mapping (blue curve).

| Target | Functional check and interpretation |
|---|---|
| Authalic mapping | Equal-area interpretation follows analytically from the authalic construction; implementation tests give sub-nanometre equivalent meridional round-trip error. |
| Converter execution | End-to-end conversions completed successfully across EO and climate product types (Sentinel-2, Sentinel-3, ERA5, CAMS, DestinE Climate DT); the Sentinel-2 EOPF workflow was also deployed in a containerised cloud environment. |
| Resampling execution | Nearest-neighbour and PSF/multi-point weighted mappings exercised on CPU and CUDA-enabled GPU using synthetic point clouds. |

Table 3. Representative functional checks and current implementation status.

## 6. Interoperability and Metadata Conventions

Grid4Earth is an implementation ecosystem built on published DGGS standards and conventions rather than a proposal for a new standard. It implements hierarchical cells, refinement levels, and unique identifiers in accordance with DGGS concepts. OGC Topic 21 defines DGGS as spatial reference systems using hierarchical tessellations to partition and address the globe (Open Geospatial Consortium, 2021). OGC API – DGGS Part 1: Core is a published standard for accessing data organised according to DGGS reference systems (Open Geospatial Consortium, 2025). Grid4Earth HEALPix/Zarr products are designed for exposure through such APIs; service implementation and formal registration of ellipsoidal HEALPix as a DGGS reference system are the next OGC integration steps.

Metadata is central because a spherical HEALPix product and an ellipsoidal WGS84 HEALPix product may have the same cell identifiers but different geodetic interpretations. Grid4Earth therefore records the reference body, indexing

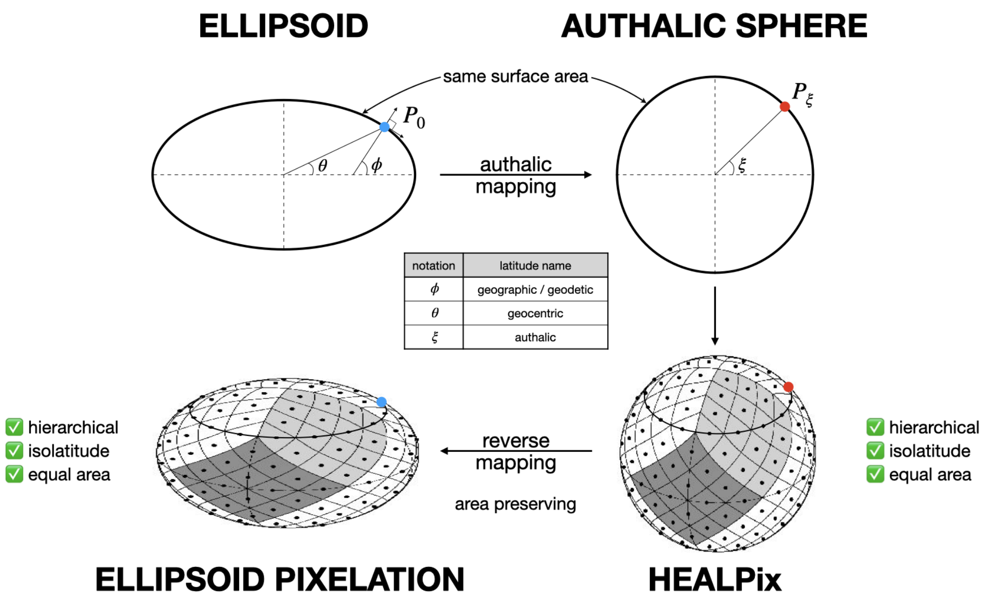


Figure 3. Equal-area-preserving extension of HEALPix to an ellipsoid of revolution (e.g. WGS84) through an authalic-latitude mapping.

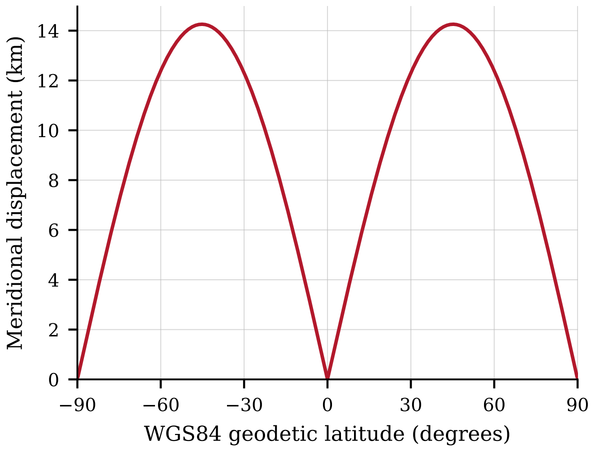


Figure 4. Magnitude of the meridional displacement between the spherical and WGS84 interpretations of identical HEALPix cell indices, plotted against WGS84 geodetic latitude. The displacement results from the authalic-to-geodetic latitude conversion and reaches approximately 14.2 km near $\pm 45°$. HEALPix level 8 is used for sampling; the mapping itself is not level-dependent.

scheme, refinement level, and coordinate variable. The current implementation follows the HEALPix grid mapping published in CF Conventions 1.13 (CF Community, 2025) and the metadata structure defined by version 1 of the Pilot Zarr DGGS convention (Zarr-conventions contributors, 2026).

For EO products, compatibility with EOPF-style Zarr group structures and SpatioTemporal Asset Catalog (STAC)-like discovery metadata is important, because EOPF provides ESA's harmonised framework for re-engineering Copernicus Sentinel processing and product organisation (European Space Agency, 2026). Multi-resolution Sentinel bands can be stored as distinct Zarr groups or pyramid levels, each with explicit refinement metadata and aggregation semantics. Discovery metadata should describe source mission, processing level, time, footprint, and DGGS grid information, so that users can find products without knowing the internal chunk layout.

Grid4Earth implements the relevant metadata fields defined by CF 1.13 and version 1 of the Pilot Zarr DGGS convention, including the HEALPix grid mapping, cell identifiers, indexing schemes, refinement levels, ellipsoid metadata, the HEALPix index coordinate, and Zarr-based output. In this paper, implementation denotes alignment of the generated metadata with these published field definitions; it does not imply conformance of an OGC API service. The Zarr DGGS convention is currently classified as a Pilot convention. OGC service integration remains future work. Table 4 summarises the distinction between the maturity of each specification and the current Grid4Earth implementation status.

## 7. Discussion and Outlook

The choice of ellipsoidal HEALPix reflects a deliberate trade-off among mature DGGS options. H3 and S2 remain widely used systems for web-scale spatial indexing, hexagonal grids such as ISEA variants offer attractive neighbourhood relations for graph-based analysis, and rHEALPix provides an alternative ellipsoidal equal-area design. Grid4Earth's choice is driven by the requirements of EO and Digital Twin Earth workflows: equal-area global statistics, multi-resolution data cubes, cloud-native chunking, and compatibility with spherical-harmonic analysis on the authalic sphere. Through this representation, `healpix-analyse` provides spherical-harmonic transforms, power spectra, convolutional operators, and multi-resolution operations for fields in the Grid4Earth data model. This shared spectral representation is what allows climate model outputs and EO observations – despite their different native geometries – to be compared and jointly analysed on the same ellipsoidal HEALPix grid. As noted in Section 5, these operations apply to authalic-mapped fields and should not be interpreted as intrinsic ellipsoidal harmonics.

The core packages are public and documented for research, tutorials, and prototyping. Native support in desktop GIS

| Area | Current status in Grid4Earth | Maturity |
|---|---|---|
| DGGS model | HEALPix refinement levels, cell identifiers, NESTED indexing and region coverage through `healpix-geo`. | Implemented and documented |
| Ellipsoid metadata | Reference body, WGS84 parameters and indexing scheme recorded explicitly in HEALPix/Zarr products. | Implemented; transformation consistency checked |
| Zarr/EOPF layout | HEALPix-indexed Zarr outputs and group-based multi-resolution representation compatible with EOPF-style structures, exercised across Sentinel-2, Sentinel-3, ERA5, CAMS and DestinE Climate DT products. | Implemented and exercised across five product types |
| CF metadata | CF 1.13 defines the HEALPix grid mapping, indexing schemes, refinement level, and HEALPix index coordinate; Grid4Earth implements these metadata fields. | Published convention; relevant fields implemented |
| OGC DGGS/API | OGC API – DGGS Part 1: Core is published; Grid4Earth service implementation and formal ellipsoidal HEALPix registration are the next integration steps. | Standard published; service integration and registration planned |
| Pilot Zarr DGGS convention | Grid4Earth implements the metadata structure defined by version 1 of the convention, including the DGGS object and array organisation. | Pilot convention; metadata structure implemented |

Table 4. Metadata and interoperability status of the Grid4Earth ecosystem. The table distinguishes specification maturity, implemented metadata fields, and planned OGC service-integration steps.

tools such as QGIS or GDAL represents an additional integration opportunity for the broader HEALPix/Zarr community. Grid4Earth is intended for workflows spanning projection zones, combining EO with climate or auxiliary data, or requiring equal-area statistics and a common global cell-identifier coordinate.

Together, these implementation checks demonstrate numerical consistency of the authalic coordinate transformations, end-to-end integration of the software components in the tested environment, and functional coverage across multiple product types. They establish Grid4Earth as a reusable software foundation for broader EO and climate workflows.

## 8. Conclusions

This paper presented Grid4Earth, an open-source Python ecosystem that uses ellipsoidal HEALPix as a common representation connecting spherical climate and Digital Twin Earth model outputs with ellipsoidal EO observations, and that makes this representation practical through reusable, ellipsoid-aware indexing, resampling, visualisation and analysis tools. The ecosystem combines `healpix-geo` for ellipsoid-aware indexing and coverage, with WGS84 as the default reference ellipsoid for EO products, `healpix-resample` for sparse CPU/GPU-capable regridding, `healpix-plot` for visualisation, and `healpix-analyse` for diagnostics. A project-level package registry supports consistent installation of the complete stack. A separately developed converter package, built on these components, demonstrates that this ecosystem can be applied to real EO and climate data processing.

Building on previous DGGS comparisons, XDGGS, and cloud-native DGGS service work, Grid4Earth addresses the implementation gap needed to make HEALPix practical for EO data: ellipsoidal geodetic interpretation, HEALPix/Zarr organisation, and reusable Python tools for conversion and analysis. The equal-area interpretation follows analytically from the authalic construction, while implementation checks demonstrate numerical consistency of the coordinate transformations and execution of the workflow in the tested environment.

Grid4Earth contributes software and implementation experience to DGGS metadata and interoperability discussions, including CF Conventions, the Pilot Zarr DGGS convention, EOPF-compatible structures, and OGC DGGS access patterns. Further work will include product-scale validation, broader Sentinel and DestinE demonstrations, public release and documentation of the converter package, and persistent software citations.

## Code and Data Availability

The public software components are available from the GRID4EARTH GitHub organisation: `healpix-geo`, `healpix-resample`, `healpix-plot`, `healpix-analyse`, and the `packages` registry. The registry provides curated requirements files and environment specifications for reproducible installation of a consistent Grid4Earth stack. Released versions are archived on Zenodo with persistent software DOIs. A converter package built on these components has been exercised across five EO and climate product types. The converter is currently being prepared for public release; its source code and versioned configurations will be made available through the GRID4EARTH GitHub organisation.

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