healsparse

Eli Rykoff and Javier Sanchez

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HealSparse is a sparse implementation of HEALPix in Python, written for the Rubin Observatory Legacy Survey of Space and Time Dark Energy Science Collaboration (DESC). *HealSparse* is a pure Python library that sits on top of numpy and hpgeom and is designed to avoid storing full sky maps in case of partial coverage, including easy reading of sub-maps. This reduces the overall memory footprint allowing maps to be rendered at arcsecond resolution while keeping the familiarity and power of HEALPix.

HealSparse expands on functionality available in healpy and straight HEALPix maps by allowing maps of different data types, including 32- and 64-bit floats; 8-, 16-, 32-, and 64-bit integers; "wide bit masks" of arbitrary width (allowing hundreds of bits to be efficiently and conveniently stored); and numpy record arrays. Arithmetic operations between maps are supported, including sum, product, min/max, and and/or/xor bitwise operations for integer maps. In addition, there is general support for any numpy universal function.

HealSparse also includes a simple geometric primitive library, to render circles and convex polygons.

The code is hosted in GitHub. Please use the issue tracker to let us know about any problems or questions with the code. The list of released versions of this package can be found here, with the main branch including the most recent (non-released) development.

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CHAPTER

ONE

INSTALL

HealSparse requires hpgeom, numpy, and astropy. If you have fitsio installed then additional features including memory-efficient concatenation of *HealSparse* maps are made available. Installation of healpy is required for reading full maps in HEALPix format.

HealSparse is available at pypi and conda-forge, and the most convenient way of installing the latest released version is simply:

```
conda install -c conda-forge hpgeom
```

or

```
pip install healsparse
```

To install from source, you can run from the root directory:

```
pip install .
```

CHAPTER

TWO

QUICKSTART

A jupyter notebook is available for tutorial purposes here

CHAPTER

THREE

BASIC HEALSPARSE INTERFACE

3.1 Getting Started

To conserve memory, *HealSparse* uses a dual-map approach, where a low-resolution full-sky "coverage map" is combined with a high resolution map containing the pixel data where it is available. The resolution of the coverage map is controlled by the `nside_coverage` parameter, and the resolution of the high-resolution map is controlled by the `nside_sparse` parameter. Behind the scenes, *HealSparse* uses clever indexing to allow the user to treat these as contiguous maps with minimal overhead. **All HealSparse maps use HEALPix nest indexing behind the scenes, should be treated as nest-indexed maps.**

There are 3 basic ways to make a `HealSparseMap`. First, one can read in an existing *HEALPix* map; second, one can read in an existing `HealSparseMap`; and third, one can create a new map.

```
import numpy as np
import healsparse

# To read a HEALPix map, the nside_coverage must be specified
map1 = healsparse.HealSparseMap.read('healpix_map.fits', nside_coverage=32)

# To read a healsparse map, no additional keywords are necessary
map2 = healsparse.HealSparseMap.read('healsparse_map.hs')

# To read part of a healsparse map, you can specify the coverage pixels to read
map2_partial = healsparse.HealSparseMap.read('healsparse_map.hs', pixels=[100, 101])

# To create a new map, the resolutions and datatype must be specified
nside_coverage = 32
nside_sparse = 4096
map3 = healsparse.HealSparseMap.make_empty(nside_coverage, nside_sparse, np.float64)
```

To set values in the map, you can use simple indexing or the explicit API:

```
map3[0: 1000] = np.arange(1000, dtype=np.float64)
map3.update_values_pix(np.arange(1000, 2000), np.arange(1000, dtype=np.float64),␣
↪nest=True)
```

To retrieve values from the map, you can use simple indexing or the explicit API via pixels or positions:

```
print(map3[0: 1000])
>>> [0. ... 999.]
print(map3.get_values_pix(np.arange(1000, 2000), nest=True))
```

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```
>>> [0. ... 999.]
print(map3.get_values_pos(45.0, 0.1, lonlat=True))
>>> 51.0
```

A HealSparseMap has the concept of "valid pixels", the pixels over which the map is defined (as opposed to hpgeom.UNSEEN in the case of floating point maps). You can retrieve the array of valid pixels or the associated positions of the valid pixels easily:

```
print(map3.valid_pixels)
>>> [   0    1    2 ... 1997 1998 1999]

ra, dec = map3.valid_pixels_pos(lonlat=True)
print(ra)
>>> [45.         ... 45.3515625 ]
print(dec)
>>> [0.00932548 ... 0.81134431]
```

You can convert a HealSparseMap to a healpy map (numpy array) either by using a full slice ([:]) or with the generate_healpix_map() method. Do watch out, at high resolution this can blow away your memory! In these cases, generate_healpix_map() can degrade the map before conversion, using a reduction function (over valid pixels) of your choosing, including mean, median, std, max, min, and, or, sum, prod (product), and wmean (weighted mean).

```
hpmap4096 = map3[:]
hpmap128 = map3.generate_healpix_map(nside=128, reduction='mean')
```

3.2 Integer Maps

In addition to floating-point maps, which are natively supported by healpy, HealSparseMap supports integer maps. The "sentinel" value of these maps (equivalent to hpgeom.UNSEEN) is either -MAXINT or 0, depending on the desired use of the map (e.g., integer values or positive bitmasks). Note that these maps cannot be trivially converted to healpy maps because *HEALPix* has no concept of sentinel values that are not hpgeom.UNSEEN, which is a very large negative floating-point value.

```
import numpy as np
import healsparse

map_int = healsparse.HealSparseMap.make_empty(32, 4096, np.int32)
print(map_int)
>>> HealSparseMap: nside_coverage = 32, nside_sparse = 4096, int32

map_int[0: 1000] = np.arange(1000, dtype=np.int32)

print(map_int[500])
>>> 500
```

3.3 Recarray Maps

HealSparseMap also supports maps made up of numpy record arrays. These recarray maps will have one field that is the "primary" field which is used to test if a pixel has a valid value or not. Therefore, these recarray maps should be used to describe associated values that share the exact same valid footprint. Each field in the recarray can be treated as its own HealSparseMap. For example,

```
import numpy as np
import healsparse

dtype = [('a', np.float32), ('b', np.int32)]

map_rec = healsparse.HealSparseMap.make_empty(32, 4096, dtype, primary='a')

map_rec[0: 10000] = np.zeros(10000, dtype=dtype)
print(map_rec.valid_pixels)
>>> [   0    1    2 ... 9997 9998 9999]

map_rec['a'][0: 5000] = np.arange(5000, dtype=np.float32)
map_rec['b'][5000: 10000] = np.arange(5000, dtype=np.int32)

print(map_rec[map_rec.valid_pixels])
>>> [(0.,    0) (1.,    0) (2.,    0) ... (0., 4997) (0., 4998) (0., 4999)]
```

Note that the call `map_rec['a'][0:  5000] = values` will work, but `map_rec[0:  5000]['a'] = values` will not. Also note that using the fields of the recarray *cannot* be used to set new pixels, this construction can only be used to change pixel values.

3.4 Wide Masks

HealSparse has support for "wide" bit masks with an arbitrary number of bits that are referred to by bit position rather than value. This is useful, for example, when constructing a coadd coverage map where every pixel can uniquely identify the set of input exposures that contributed at the location of that pixel. In the case of >64 input exposures you can no longer use a simple 64-bit integer bit mask. Wide mask bits are always specified by giving a list of integer positions rather than values (e.g., use `10` to set the 10th bit instead of `1024 = 2**10`).

```
import numpy as np
import healsparse

map_wide = healsparse.HealSparseMap.make_empty(32, 4096, healsparse.WIDE_MASK, wide_mask_
↪maxbits=128)

pixels = np.arange(10000)
map_wide.set_bits_pix(pixels, [4, 100])

print(map_wide.check_bits_pix(pixels, [2]))
>>> [False False False ... False False False]
print(map_wide.check_bits_pix(pixels, [4]))
>>> [ True  True  True ...  True  True  True]
print(map_wide.check_bits_pix(pixels, [100]))
>>> [ True  True  True ...  True  True  True]
```

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```
print(map_wide.check_bits_pix(pixels, [101]))
>>> [False False False ... False False False]

# Check if any of the bits are set
print(map_wide.check_bits_pos([45.2], [0.2], [100, 101], lonlat=True))
>>> [ True]
```

3.5 Writing Maps

Writing a HealSparseMap is easy. To write a map in the default FITS format:

```
map3.write('output_file.hs', clobber=False)
```

And to write a map in the Parquet format with pyarrow:

```
map3.write('output_file.hsparquet', clobber=False, format='parquet')
```

3.6 Metadata

You can also set key/value metadata to a map that will be stored in the fits header of the file and read back in. The keys must confirm to FITS header key standards (strings, upper case). The metadata will be stored as a Python dictionary, and can be accessed with the metadata property.

```
metadata = {'KEY1': 5, 'KEY2': 10.0}
map3.metadata = metadata
print(map3.metadata['KEY2'])
>>> 10.0
```

3.7 Coverage Masks

A HealSparseMap contains a coverage map that defines the coarse coverage over the sky. You can retrieve a boolean array describing which pixels are covered in the map with the coverage_mask property:

```
import hpgeom as hpg
import matplotlib.pyplot as plt

cov_mask = map3.coverage_mask
cov_pixels, = np.where(cov_mask)
ra, dec = hpg.pixel_to_angle(map3.nside_coverage, cov_pixels)
plt.plot(ra, dec, 'r.')
plt.show()
```

It is also possible to read the coverage map of a HealSparseMap on its own:

```
cov_map = healsparse.HealSparseCoverage.read('output_file.hs')
cov_mask = cov_map.coverage_mask
```

In some cases, you may be building a map and you already know the coverage when it will be finished. In this case, it can be faster to initialize the memory at the beginning. In this case, you can add `cov_pixels` to the `make_empty` call. Be aware this may make the map larger than your actual coverage.

```
import healsparse

nside_coverage = 32
nside_sparse = 4096
map4 = healsparse.HealSparseMap.make_empty(nside_coverage, nside_sparse, np.float32,
                                           cov_pixels=[5, 10, 20, 21])
```

3.8 Fractional Detection Maps

One can compute the fractional detection map of a `HealSparseMap` with the `fracdet_map()` method. This method will compute the fractional area covered by the sparse map at an arbitrary resolution (not higher than the native resolution, and not lower than the coverage map `nside_coverage`). This is a count of the fraction of "valid" sub-pixels (those that are not equal to the sentinel value) in the original map. These maps can be useful in conjunction with a degraded map to easily determine the coverage fraction of each degraded pixel.

In order to translate a `fracdet_map` to lower resolution, the `degrade()` method should be used with the default "mean" reduction operation. If one tries to compute the `fracdet_map` of an existing `fracdet_map` then you will not get the expected output, because this is the fractional coverage of the `fracdet_map` itself, not of the original sparse map.

3.9 Basic Visualization

`healsparse` does not provide any built-in visualization tools. However, it is possible to perform quick visualizations of a `HealSparseMap` using the `matplotlib` package. For example, we can take render our map as a collection of hexagonal cells using `matplotlib.pyplot.hexbin`:

```
import healsparse
import matplotlib.pyplot as plt

nside_coverage = 32
nside_sparse = 4096

# Generation of the map
hsp_map = healsparse.HealSparseMap.make_empty(nside_coverage, nside_sparse, np.float32)
idx = np.arange(2000, 6000)
hsp_map[idx] = np.random.uniform(size=idx.size).astype(np.float32)

# Visualization of the map
vpix, ra, dec = hsp_map.valid_pixels_pos(return_pixels=True)
plt.hexbin(ra, dec, C=hsp_map[vpix])
plt.colorbar()
plt.show()
```

CHAPTER

FOUR

HEALSPARSE MAP OPERATIONS

4.1 Introduction

HealSparse has support for basic arithmetic operations between maps, including sum, product, min/max, and and/or/xor bitwise operations for integer maps. In addition, there is general support for any `numpy` universal function. It is important to note that map operations are complicated by the fact that any given maps may not have the same pixel coverage. Therefore, map operations can be done either with "union" (where the final map has a valid pixel list that is the union of the input maps) or "intersection" (where the final map has a valid pixel list that is the intersection of the input maps). In the case of "union" operations, the maps that do not have coverage at a given point will be filled with an appropriate value (for example, 0 for summation and 1 for products).

4.2 Operations With a Constant

Arithmetic operations with a constant are very simple, and are handled with the default Python operations, supporting copy or in-place operations.

```
import numpy as np
import healsparse

map_float = healsparse.HealSparseMap.make_empty(32, 4096, np.float64)
map_float[0: 10000] = np.zeros(1, dtype=np.float64)

print(map_float[0: 10000])
>>> [0. 0. 0. ... 0. 0. 0.]

map_float += 10.0
print(map_float[0: 10000])
>>> [10. 10. 10. ... 10. 10. 10.]

map_float /= 10.0
print(map_float[0: 10000])
>>> [1. 1. 1. ... 1. 1. 1.]

map_float2 = map_float*100.0
print(map_float[0: 10000])
>>> [1. 1. 1. ... 1. 1. 1.]
print(map_float2[0: 10000])
>>> [100. 100. 100. ... 100. 100. 100.]
```

4.3 Operations With Multiple Maps

Operations between maps can be done with either "union" or "intersection" mode. The basic operations supported are `sum`, `product`, `divide`, `floor_divide`, `min`, `max`, `or`, `and`, `xor`, and `ufunc`. Note that `or`, `and`:, and `xor` operations are only supported for integer maps. Note that operations between maps are only supported if they have the same `nside_sparse` resolution and data type. In all cases except division, the function name is `operation_union()` or `operation_intersection()`. The division routines only support intersection operations. For example,

```
import numpy as np
import healsparse

map1 = healsparse.HealSparseMap.make_empty(32, 4096, np.float64)
map1[0: 10000] = np.ones(10000)
map2 = healsparse.HealSparseMap.make_empty_like(map1)
map2[5000: 15000] = np.ones(10000)*5.0

# The union sum will have coverage that was from map1 OR map2
sum_union = healsparse.operations.sum_union([map1, map2])
print(sum_union[sum_union.valid_pixels].min())
>>> 1.0
print(sum_union[sum_union.valid_pixels].max())
>>> 6.0
print(sum_union.valid_pixels.min(), sum_union.valid_pixels.max())
>>> 0 14999

# The intersection sum will have coverage that was from map1 AND map2
sum_intersection = healsparse.operations.sum_intersection([map1, map2])
print(sum_intersection[sum_intersection.valid_pixels].min())
>>> 6.0
print(sum_intersection[sum_intersection.valid_pixels].max())
>>> 6.0
print(sum_intersection.valid_pixels.min(), sum_intersection.valid_pixels.max())
>>> 5000 9999
```

CHAPTER

FIVE

HEALSPARSE GEOMETRY

HealSparse has a basic geometry library that allows you to generate maps from circles and convex polygons, as supported by healpy. Each geometric object is associated with a single value. On construction, geometry objects only contain information about the shape, and they are only rendered onto a *HEALPix* grid when requested.

There are two methods to realize geometry objects. The first is that each object can be used to generate a HealSparseMap map, and the second, for integer-valued objects is the realize_geom() method which can be used to combine multiple objects by or-ing the integer values together.

5.1 HealSparse Geometry Shapes

The three shapes supported are Circle, Ellipse, and Polygon. They share a base class, and while the instantiation is different, the operations are the same.

Circle

```
import healsparse

# All units are decimal degrees
circ = healsparse.Circle(ra=200.0, dec=0.0, radius=1.0, value=1)
```

Ellipse

```
import healsparse

# All units are decimal degrees
# The inclination angle alpha is defined counterclockwise with respect to North.
# See https://hpgeom.readthedocs.io/en/latest .
ellipse = healsparse.Ellipse(ra=200.0, dec=0.0, semi_major=1.0, semi_minor=0.5, alpha=45.
↪0, value=1)
```

Convex Polygon

```
# All units are decimal degrees
poly = healsparse.Polygon(ra=[200.0, 200.2, 200.3, 200.2, 200.1],
                          dec=[0.0, 0.1, 0.2, 0.25, 0.13],
                          value=8)
```

5.2 Making a Map

To make a map from a geometry object, use the `get_map()` method as such. The higher resolution you choose, the better the aliasing at the edges (given that these are pixelized approximations of the true shapes). You can also combine two maps using the general operations. Note that if the polygon is an integer value, the default sentinel when using `get_map()` is `0`.

```
smap_poly = poly.get_map(nside_coverage=32, nside_sparse=32768, dtype=np.int16)
smap_circ = circ.get_map(nside_coverage=32, nside_sparse=32768, dtype=np.int16)

combo = healsparse.or_union([smap_poly, smap_circ])
```

5.3 Using `realize_geom()`

You can only use `realize_geom()` to create maps from combinations of polygons if you are using integer maps, and want to `or` them together. This method is more memory efficient than generating each individual individual map and combining them, as above.

```
realized_combo = healsparse.HealSparseMap.make_empty(32, 32768, np.int16, sentinel=0)
healsparse.realize_geom([poly, circ], realized_combo)
```

CHAPTER

SIX

HEALSPARSE RANDOMS

HealSparse can generate uniform randoms based on the valid pixels in a HealSparseMap map. It is up to the user of these random points to weight them appropriately.

There are two methods to generate randoms. The "fast" method requires more memory, and produces randoms that are quantized (at a very high level). The regular method is not quantized and does not require any extra memory, but is significantly slower.

6.1 Fast Random Generation

The fast random generation is run with `healsparse.make_uniform_randoms_fast()`. This code path requires more memory and may not be suitable for very large, high resolution masks. The output randoms are quantized by the `nside_randoms` quantity. The default is `2**23`, which is approximately 7e-6 arcsecond quantization, which should be adequate for most purposes.

```
import healsparse

circ = healsparse.Circle(ra=200.0, dec=0.0, radius=1.0, value=1)
smap = circ.get_map(nside_coverage=32, nside_sparse=32768, dtype=np.int16)

# Make 100000 randoms
ra_rand, dec_rand = healsparse.make_uniform_randoms_fast(smap, 100000)
```

6.2 Regular Random Generation

The regular random generation is run with `healsparse.make_uniform_randoms()`. This code requirest less memory than the fast generation, and there is no quanitization in the random points. However, it is slower than the fast generation. The API is very similar to `healsparse.make_uniform_randoms_fast()`.

```
import healsparse

circ = healsparse.Circle(ra=200.0, dec=0.0, radius=1.0, value=1)
smap = circ.get_map(nside_coverage=32, nside_sparse=32768, dtype=np.int16)

# Make 100000 randoms
ra_rand, dec_rand = healsparse.make_uniform_randoms(smap, 100000)
```

CHAPTER

SEVEN

CONCATENATION OF HEALSPARSE FILES

HealSparse contains a routine for concatenating (combining) multiple HealSparseMap files. If fitsio is available, this will be done in a memory-efficient way. In this way, multiple non-overlapping maps can be combined. This makes possible a simple parallelized scatter-gather approach to creating complex survey maps, where individual tiles are run independently, and then all combined at the end.

7.1 Using cat_healsparse_files()

The cat_healsparse_files() routine takes in a list of filename, and an output filename. The individual files must have the same nside_sparse, but may have different nside_coverage. The output file will have the same nside_coverage as the first input file unless otherwise specified.

By default, for speed, the code will not check that the input HealSparseMap files are non-overlapping (that is, that they do not share valid_pixels; they may share coverage in the coverage map). This can be checked.

If fitsio is available (recommended), the combination is not done in-memory. This behavior can be modified by the user by setting in_memory to True. However, if only astropy.io.fits is available for FITS interfacing, the concatenation can only be done in-memory (and the in_memory value should be overridden.

```
import healsparse

healsparse.cat_healsparse_files(file_list, outfile, check_overlap=False, clobber=False,
                                in_memory=False, nside_coverage_out=None)
```

CHAPTER

EIGHT

HEALSPARSEMAP FILE SPECIFICATION V1.4.0

A `HealSparseMap` file can be either a standard FITS file or a Parquet dataset. Each provides a way to record the data from a `HealSparseMap` object for efficient retrieval of individual coverage pixels. This document describes the memory layout of the key components of the `HealSparseMap` objects, as well as the specific file formats in FITS (*HealSparseMap FITS Serialization*) and Parquet (*HealSparseMap Parquet Serialization*).

CHAPTER

NINE

HEALSPARSEMAP MEMORY LAYOUT

A `HealSparseMap` object has two primary components, the coverage map and the sparse map.

9.1 Terminology

This is a list of terminology used in a `HealSparseMap` object:

- `nside_sparse`: The *HEALPix* nside for the fine-grained (sparse) map
- `nside_coverage`: The *HEALPix* nside for the coverage map
- `bit_shift`: The number of bits to shift to convert from `nside_sparse` to `nside_coverage` in the *HEALPix* NEST scheme. `bit_shift = 2*log_2(nside_sparse/nside_coverage)`.
- `valid_pixels`: The list of pixels with defined values (> `sentinel`) in the sparse map.
- `sentinel`: The sentinel value that notes if a pixel is not a valid pixel. Default is `hpgeom.UNSEEN` for floating-point maps, `-MAXINT` for integer maps, and `0` for wide mask maps.
- `nfine_per_cov`: The number of fine (sparse) pixels per coverage pixel. `nfine_per_cov = 2**bit_shift`.
- `wide_mask_width`: The width of a wide mask, in bytes.

9.2 Pixel Lookups

The `HealSparseMap` file format is derived from the method of encoding fast look-ups of arbitary pixel values using the *HEALPix* nest pixel scheme.

Given a nest-encoded sparse (high resolution) pixel value, `pix_nest`, we can compute the coverage (low resolution) pixel value with a simple bit shift operation: `ipnest_cov = right_shift(pix_nest, bit_shift)`, where `bit_shift` is defined in *Terminology*.

The sparse map itself is stored in blocks of data, each of which includes `nfine_per_cov` contiguous pixels for each coverage pixel that contains valid data. To find the location *within* a given a coverage block, we need to subtract the first fine (sparse) nest pixel value for the given coverage pixel. Therefore, `first_pixel = nfine_per_cov*ipnest_cov`.

Next, if we have a map of offsets which points to the location of the proper sparse map block, `cov_map_raw_offset`, we find the look-up index is `index = pix_nest - nfine_per_cov*ipnest_cov + cov_map_raw_offset[ipnest_cov]`. In practice, we can combine the final terms here. The look-up index is then `index = pix_nest + cov_map[ipnest_cov]` where `cov_map = cov_map_raw_offset[ipnest_cov] - nfine_per_cov*ipnest_cov`.

As described in *Sparse Map*, the first block in the sparse map is special, and is always filled with `sentinel` values. All `cov_map` indices for coverage pixels outside the coverage map point to this sentinel block.

9.3 Coverage Map

The coverage map encodes the mapping from raw pixel number to location within the sparse map. It is an integer (`numpy.int64`) map with `12*nside_coverage*nside_coverage` values, all of which are filled.

As described in *Pixel Lookups*, the coverage map contains indices that are offset pointers to the block in the sparse map with associated values for that coverage pixel. An empty `HealSparseMap` is intialized with the following coverage pixel values, which all point to the first `sentinel` block in the sparse map.

```
import numpy as np
import hpgeom as hpg

cov_map[:] = -1*np.arange(hpg.nside_to_npixel(nside_coverage), dtype=np.int64)*nfine_per_
↪cov
```

9.4 Sparse Map

The sparse map contains the map data, split into blocks, each of which is `nfine_per_cov` elements long. The first block is special, and is always filled with `sentinel` values.

The following datatypes are allowed:

- 1-byte unsigned integer (`numpy.uint8`)
- 1-byte signed integer (`numpy.int8`)
- 2-byte unsigned integer (`numpy.uint16`)
- 2-byte signed integer (`numpy.int16`)
- 4-byte unsigned integer (`numpy.uint32`)
- 4-byte signed integer (`numpy.uint32`)
- 8-byte signed integer (`numpy.int64`)
- 4-byte floating point (`numpy.float32`)
- 8-byte floating point (`numpy.float64`)
- Numpy record array of numeric types that can be serialized with FITS
- The `WIDE_MASK` special encoding

Sparse Map Image

If the sparse map is a single datatype, it is held in memory as a one-dimensional image array. The first block of `nfine_per_cov` values are set to `sentinel`. Each additional block of `nfine_per_cov` is associated with a single element in the coverage map. These blocks may be in any arbitrary order, allowing for easy appending of new coverage pixels. All invalid pixels must be set to `sentinel`.

Sparse Map Wide Mask

If the sparse map is a wide mask map, the sparse map is held in memory as a `wide_mask_width * npix` array. The sentinel value for wide masks must be `0`, and all invalid pixels must be set to `0`.

Sparse Map Table

If the sparse map is a numpy record array type, it is held in memory as a one dimensional table array. The first block of `nfine_per_cov` values are set such that the `primary` field must be set to `sentinel`. As with the sparse map image, each additional block of `nfine_per_cov` is associated with a single element in the coverage map. These blocks may

be in any arbitrary order, allowing for easy appending of new coverage pixels. All invalid pixels must have the `primary` field set to `sentinel`.

CHAPTER

TEN

HEALSPARSEMAP FITS SERIALIZATION

A `HealSparseMap` FITS file is a standard FITS file with two extensions. The primary (zeroth) extension is an integer image that describes the coverage map, and the first extension is an image or binary table that describes the sparse map. This section describes the file format specification of these two extensions in the FITS file.

10.1 Coverage Map

Coverage Map Header

The coverage map header must contain the following keywords:

- **EXTNAME** must be `"COV"`
- **PIXTYPE** must be `"HEALSPARSE"`
- **NSIDE** is equal to `nside_coverage`

Coverage Map Image

The FITS coverage map is a direct serialization of the coverage map image in-memory layout described in *Coverage Map*.

Sparse Map Header

The sparse map header must contain:

- **EXTNAME** must be `"SPARSE"`
- **PIXTYPE** must be `"HEALSPARSE"`
- **SENTINEL** is equal to `sentinel`
- **NSIDE** is equal to `nside_sparse`

If the sparse map is a numpy record array, it must contain:

- **PRIMARY** is equal to the name of the "primary" field which defines the valid pixels.

If the sparse map is a wide mask, it must contain:

- **WIDEMASK** must be `True`
- **WWIDTH** must be the width (in bytes) of the wide mask.

Sparse Map Image

If the sparse map is not of a numpy record array type, it is stored as a one dimensional image array. If the image is an integer type with 32 bits or fewer, it may be stored with FITS tile compression, with the tile size set to

the block size (nfine_per_cov). If the image is a floating-point image, it may be stored with FITS tile compression, with quantization_level=0 and GZIP_2 (lossless gzip compression), with the tile size set to the block size (nfine_per_cov).

Sparse Map Wide Mask

If the sparse map is a wide mask map, the sparse map is stored as a flattened version of the in-memory wide_mask_width * npix array. This should be flattened on storage, and reshaped on read, using the default numpy memory ordering. The wide mask image may be stored with FITS tile compression, with the tile size set to the block size times with width (wide_mask_width * nfine_per_cov).

Sparse Map Table

If the sparse map is a numpy record array type, it is stored as a one dimensional table array.

CHAPTER

ELEVEN

HEALSPARSEMAP PARQUET SERIALIZATION

A `HealSparseMap` serialized as Parquet is sharded as a Parquet dataset for efficient access to sub-regions of very large area, high resolution maps. The `HealSparseMap` Parquet dataset consists of a directory with two metadata files; the coverage map; and a list of low resolution "i/o pixel" directories (default `nside_io=4`). In each i/o pixel directory is a Parquet file with all of the sparse map data from that i/o pixel, divided into Parquet row groups for each coverage pixel. The `HealSparseMap` Parquet format uses the default `snappy` per-column compression.

11.1 Parquet File Structure

11.2 Parquet Metadata

The `metadata` is stored separately in the *_metadata* and *_common_metadata* files in the dataset directory, as per the Parquet dataset specification. The `metadata` is stored as a set of key-value pairs, each of which is a binary string. For simplicity we describe the strings here as regular strings, but beware that behind the scenes they are stored in the python `b'string'` format.

The following metadata strings are required: * `'healsparse::version'`: `'1'` * `'healsparse::nside_sparse'`: `str(nside_sparse)` * `'healsparse::nside_coverage'`: `str(nside_coverage)` * `'healsparse::nside_io'`: `str(nside_io)` * `'healsparse::filetype'`: `'healsparse'` * `'healsparse::primary'`: `'primary'` or `''` * `'healsparse::sentinel'`: `str(sentinel)` or `'UNSEEN'` * `'healsparse::widemask'`: `'True'` or `'False'` * `'healsparse::wwidth'`: `str(wide_mask_width)` or `'1'`

Note that the string `'UNSEEN'` will use the special value `hpgeom.UNSEEN` to fill empty/overflow pixels.

Additional metadata from the map is stored as a FITS header string (for compatibility with the FITS serialization) such that: * `'healsparse::header'`: `header_string`

11.3 Parquet Coverage Map

The coverage map is a Parquet file with the name `_coverage.parquet`, stored in the dataset directory. The coverage map has two columns: * `cov_pix`: Valid coverage pixels (`nside = nside_coverage`) for the sparse map. * `row_group`: The row group index within the appropriate i/o pixel file to find the sparse data for the given coverage map.

11.4 Parquet Map Files

Each sparse map Parquet file covers one i/o pixel. The name of each file is `iopix=###/###.parquet`, where `###` is a zero-padded three digit number for the given i/o pixel. By putting each pixel in its own directory with this naming scheme we allow pyarrow to use the hive partitioning and only touch the files as necessary.

Each file is written as a series of Parquet row groups. Each row group contains all the data for a single coverage pixel, with `nfine_per_cov` rows per row group. The row group number within the given i/o pixel is recorded in the `_coverage.parquet` coverage map file for quick access to individual and groups of coverage pixels.

The exact format of the data depends on whether the map is a simple image, a wide mask, or a record array.

Sparse Map Image

If the sparse map is not of a numpy record array type, it is stored in a two-column Parquet table. The schema is given by: * `cov_pix`: `int32` * `sparse`: Datatype of the sparse image data.

The `cov_pix` gives the coverage pixel of the data, and is redundant with the data in `_coverage.parquet`. It compresses very efficiently, and can be used to reconstruct the `_coverage.parquet` from the data files if necessary.

The `sparse` column has the sparse map data (with sparse map image datatype).

Unlike the FITS serialization, the initial "overflow" coverage pixel is not serialized. Instead, on read this is filled in with the `sentinel` value from the Parquet metadata.

Sparse Map Wide Mask

If the sparse map is a wide mask map, the schema is the same as for a regular sparse map image. In this case, as with the FITS serialization, the sparse map is stored as a flattened version of the in-memory `wide_mask_width * npix` array. This means that there will be `wide_mask_width * nfine_per_cov` rows per row group in each wide mask Parquet file.

Sparse Map Table

If the sparse map is a numpy record array type, it is stored as a multi-column Parquet table with the following schema: * `cov_pix`: `int32` * `column_1`: Datatype of column 1. * `column_2`: Datatype of column 2. * Etc.

Unlike the FITS serialization, the initial "overflow" coverage pixel is not serialized. Instead, on read this is filled in with the `sentinel` value from the Parquet metadata for the `primary` column. The other columns in the overflow coverage pixel are filled with the default sentinel for that datatype (e.g., `hpgeom.UNSEEN` for floating-point columns and `-MAXINT` for integer columns).

CHAPTER

TWELVE

MODULES API REFERENCE

12.1 healsparse modules

12.1.1 HealSparseMap

class healsparse.healSparseMap.**HealSparseMap**(*cov_map=None*, *cov_index_map=None*, *sparse_map=None*, *nside_sparse=None*, *healpix_map=None*, *nside_coverage=None*, *primary=None*, *sentinel=None*, *nest=True*, *metadata=None*, *_is_view=False*)

Bases: `object`

Class to define a HealSparseMap

__add__(*other*)

Add a constant.

Cannot be used with recarray maps.

__and__(*other*)

Perform a bitwise and with a constant.

Cannot be used with recarray maps.

__getitem__(*key*)

Get part of a healpix map.

__iadd__(*other*)

Add a constant, in place.

Cannot be used with recarray maps.

__iand__(*other*)

Perform a bitwise and with a constant, in place.

Cannot be used with recarray maps.

__imul__(*other*)

Multiply a constant, in place.

Cannot be used with recarray maps.

__init__(*cov_map=None*, *cov_index_map=None*, *sparse_map=None*, *nside_sparse=None*, *healpix_map=None*, *nside_coverage=None*, *primary=None*, *sentinel=None*, *nest=True*, *metadata=None*, *_is_view=False*)

Instantiate a HealSparseMap.

Can be created with cov_index_map, sparse_map, and nside_sparse; or with healpix_map, nside_coverage. Also see *HealSparseMap.read()*, *HealSparseMap.make_empty()*, *HealSparseMap.make_empty_like()*.

Parameters

- **cov_map** (*HealSparseCoverage*, optional) – Coverage map object
- **cov_index_map** (*np.ndarray*, optional) – Coverage index map, will be deprecated
- **sparse_map** (*np.ndarray*, optional) – Sparse map
- **nside_sparse** (*int*, optional) – Healpix nside for sparse map
- **healpix_map** (*np.ndarray*, optional) – Input healpix map to convert to a sparse map
- **nside_coverage** (*int*, optional) – Healpix nside for coverage map
- **primary** (*str*, optional) – Primary key for recarray, required if dtype has fields.
- **sentinel** (*int* or *float*, optional) – Sentinel value. Default is *UNSEEN* for floating-point types, minimum int for int types, and False for bool types.
- **nest** (*bool*, optional) – If input healpix map is in nest format. Default is True.
- **metadata** (*dict*-like, optional) – Map metadata that can be stored in FITS header format.
- **_is_view** (*bool*, optional) – This healSparse map is a view into another healsparse map. Not all features will be available. (Internal usage)

Returns
healSparseMap

Return type
HealSparseMap

__ior__(*other*)

Perform a bitwise or with a constant, in place.

Cannot be used with recarray maps.

__ipow__(*other*)

Divide a constant, in place.

Cannot be used with recarray maps.

__isub__(*other*)

Subtract a constant, in place.

Cannot be used with recarray maps.

__itruediv__(*other*)

Divide a constant, in place.

Cannot be used with recarray maps.

__ixor__(*other*)

Perform a bitwise xor with a constant, in place.

Cannot be used with recarray maps.

__mul__(*other*)

Multiply a constant.

Cannot be used with recarray maps.

__or__(*other*)

Perform a bitwise or with a constant.

Cannot be used with recarray maps.

__pow__(*other*)

Raise the map to a power.

Cannot be used with recarray maps.

__repr__()

Return repr(self).

__setitem__(*key*, *value*)

Set part of a healpix map

__str__()

Return str(self).

__sub__(*other*)

Subtract a constant.

Cannot be used with recarray maps.

__truediv__(*other*)

Divide a constant.

Cannot be used with recarray maps.

__weakref__

list of weak references to the object (if defined)

__xor__(*other*)

Perform a bitwise xor with a constant.

Cannot be used with recarray maps.

apply_mask(*mask_map*, *mask_bits=None*, *mask_bit_arr=None*, *in_place=True*)

Apply an integer mask to the map. All pixels in the integer mask that have any bits in mask_bits set will be zeroed in the output map. The default is that this operation will be done in place, but it may be set to return a copy with a masked map.

Parameters

- **mask_map** (*HealSparseMap*) – Integer mask to apply to the map.
- **mask_bits** (*int*, optional) – Bits to be treated as bad in the mask_map. Default is None (all non-zero pixels are masked)
- **mask_bit_arr** (*list* or *np.ndarray*, optional) – Array of bit values, used if mask_map is a wide_mask_map.
- **in_place** (*bool*, optional) – Apply operation in place. Default is True

Returns

masked_map – self if in_place is True, a new copy otherwise

Return type
HealSparseMap

`astype`(*dtype*, *sentinel=None*)

Convert sparse map to a different numpy datatype, including sentinel values. If sentinel is not specified the default for the converted datatype is used (*UNSEEN* for float, and -MAXINT for ints).

Parameters

- **dtype** (*numpy.dtype*) – Valid numpy dtype for a single array.
- **sentinel** (*int* or *float*, optional) – Converted map sentinel value.

Returns
sparse_map – New map with new data type.

Return type
HealSparseMap

`check_bits_pix`(*pixels*, *bits*, *nest=True*)

Check the bits at the map for a set of pixels.

Parameters

- **pixels** (*np.ndarray*) – Integer array of healpix pixels.
- **nest** (*bool*, optional) – Are the pixels in nest scheme? Default is True.
- **bits** (*list*) – List of bits to check

Returns
bit_flags – Array of *np.bool_* flags on whether any of the input bits were set

Return type
np.ndarray

`check_bits_pos`(*ra_or_theta*, *dec_or_phi*, *bits*, *lonlat=True*)

Check the bits at the map for an array of positions. Positions may be theta/phi co-latitude and longitude in radians, or longitude and latitude in degrees.

Parameters

- **ra_or_theta** (*float*, array-like) – Angular coordinates of points on a sphere.
- **dec_or_phi** (*float*, array-like) – Angular coordinates of points on a sphere.
- **lonlat** (*bool*, optional) – If True, input angles are longitude and latitude in degrees. Otherwise, they are co-latitude and longitude in radians.
- **bits** (*list*) – List of bits to check

Returns
bit_flags – Array of *np.bool_* flags on whether any of the input bits were set

Return type
np.ndarray

`clear_bits_pix`(*pixels*, *bits*, *nest=True*)

Clear bits of a wide_mask map.

Parameters

- **pixels** (*np.ndarray*) – Integer array of sparse_map pixel values
- **bits** (*list*) – List of bits to clear

static convert_healpix_map(*healpix_map*, *nside_coverage*, *nest=True*, *sentinel=-1.6375e+30*)

Convert a healpix map to a healsparsemap.

Parameters

- **healpix_map** (*np.ndarray*) – Numpy array that describes a healpix map.
- **nside_coverage** (*int*) – Nside for the coverage map to construct
- **nest** (*bool*, optional) – Is the input map in nest format? Default is True.
- **sentinel** (*float*, optional) – Sentinel value for null values in the sparse_map.

Returns

- **cov_map** (*HealSparseCoverage*) – Coverage map with pixel indices
- **sparse_map** (*np.ndarray*) – Sparse map of input values.

property coverage_map

Get the fractional area covered by the sparse map in the resolution of the coverage map

Returns
cov_map – Float array of fractional coverage of each pixel

Return type
np.ndarray

property coverage_mask

Get the boolean mask of the coverage map.

Returns
cov_mask – Boolean array of coverage mask.

Return type
np.ndarray

degrade(*nside_out*, *reduction='mean'*, *weights=None*)

Decrease the resolution of the map, i.e., increase the pixel size.

Parameters

- **nside_out** (*int*) – Output nside resolution parameter.
- **reduction** (*str*, optional) – Reduction method (mean, median, std, max, min, and, or, sum, prod, wmean).
- **weights** (*HealSparseMap*, optional) – If the reduction is *wmean* this is the map with the weights to use. It should have the same characteristics as the original map.

Returns
healSparseMap – New map, at the desired resolution.

Return type
HealSparseMap

property dtype

get the dtype of the map

fracdet_map(*nside*)

Get the fractional area covered by the sparse map at an arbitrary resolution. This output fracdet_map counts the fraction of "valid" sub-pixels (those that are not equal to the sentinel value) at the desired nside resolution.

Note: You should not compute the fracdet_map of an existing fracdet_map. To get a fracdet_map at a lower resolution, use the degrade method with the default "mean" reduction.

Parameters
nside (*int*) – Healpix nside for fracdet map. Must not be greater than sparse resolution or less than coverage resolution.

Returns
fracdet_map – Fractional coverage map.

Return type
HealSparseMap

`generate_healpix_map`(*nside=None*, *reduction='mean'*, *key=None*, *nest=True*)

Generate the associated healpix map

if nside is specified, then reduce to that nside

Parameters

- **nside** (*int*) – Output nside resolution parameter (should be a multiple of 2). If not specified the output resolution will be equal to the parent's sparsemap nside_sparse
- **reduction** (*str*) – If a change in resolution is requested, this controls the method to reduce the map computing the "mean", "median", "std", "max", "min", "sum" or "prod" (product) of the neighboring pixels to compute the "degraded" map.
- **key** (*str*) – If the parent HealSparseMap contains recarrays, key selects the field that will be transformed into a HEALPix map.
- **nest** (*bool*, optional) – Output healpix map should be in nest format?

Returns
hp_map – Output HEALPix map with the requested resolution.

Return type
np.ndarray

`get_covpix_maps`()

Get all single covpixel maps, one at a time.

Yields
single_pixel_map (*HealSparseMap*)

`get_single`(*key*, *sentinel=None*, *copy=False*)

Get a single healsparse map out of a recarray map, with the ability to override a sentinel value.

Parameters

- **key** (*str*) – Field for the recarray
- **sentinel** (*int* or *float* or None, optional) – Override the default sentinel value. Default is None (use default)

Returns
single_map

Return type
HealSparseMap

`get_single_covpix_map`(*covpix*)

Get a healsparse map for a single coverage pixel.

Note that this makes a copy of the data.

Parameters
covpix (*int*) – Coverage pixel to copy

Returns
single_pixel_map – Copy of map with a single coverage pixel.

Return type
HealSparseMap

`get_valid_area`(*degrees=True*)

Get the area covered by valid pixels

Parameters

- **degrees** (*bool* If True (default) returns the area in square degrees,) –
- **steradians** (*if False it returns the area in*) –

Returns
valid_area

Return type
float

`get_values_pix`(*pixels*, *nest=True*, *valid_mask=False*, *nside=None*)

Get the map value for a set of pixels.

This routine will optionally convert from a higher resolution nside to the nside of the sparse map.

Parameters

- **pixel** (*np.ndarray*) – Integer array of healpix pixels.
- **nest** (*bool*, optional) – Are the pixels in nest scheme? Default is True.
- **valid_mask** (*bool*, optional) – Return mask of True/False instead of values
- **nside** (*int*, optional) – nside of pixels, if different from native. Must be greater than the native nside.

Returns
values – Array of values/validity from the map.

Return type
np.ndarray

`get_values_pos`(*ra_or_theta*, *dec_or_phi*, *lonlat=True*, *valid_mask=False*)

Get the map value for the position. Positions may be theta/phi co-latitude and longitude in radians, or longitude and latitude in degrees.

Parameters

- **ra_or_theta** (*float*, array-like) – Angular coordinates of points on a sphere.
- **dec_or_phi** (*float*, array-like) – Angular coordinates of points on a sphere.
- **lonlat** (*bool*, optional) – If True, input angles are longitude and latitude in degrees. Otherwise, they are co-latitude and longitude in radians.
- **valid_mask** (*bool*, optional) – Return mask of True/False instead of values

Returns
values – Array of values/validity from the map.

Return type
np.ndarray

property is_integer_map

Check that the map is an integer map

Returns
is_integer_map

Return type
bool

property is_rec_array

Check that the map is a recArray map.

Returns
is_rec_array

Return type
bool

property is_unsigned_map

Check that the map is an unsigned integer map

Returns
is_unsigned_map

Return type
bool

property is_wide_mask_map

Check that the map is a wide mask

Returns
is_wide_mask_map

Return type
bool

classmethod make_empty(*nside_coverage*, *nside_sparse*, *dtype*, *primary=None*, *sentinel=None*, *wide_mask_maxbits=None*, *metadata=None*, *cov_pixels=None*)

Make an empty map with nothing in it.

Parameters

- **nside_coverage** (*int*) – Nside for the coverage map
- **nside_sparse** (*int*) – Nside for the sparse map
- **dtype** (*str* or *list* or *np.dtype*) – Datatype, any format accepted by numpy.
- **primary** (*str*, optional) – Primary key for recarray, required if dtype has fields.
- **sentinel** (*int* or *float*, optional) – Sentinel value. Default is *UNSEEN* for floating-point types, and minimum int for int types.
- **wide_mask_maxbits** (*int*, optional) – Create a "wide bit mask" map, with this many bits.
- **metadata** (*dict*-like, optional) – Map metadata that can be stored in FITS header format.
- **cov_pixels** (*np.ndarray* or *list*) – List of integer coverage pixels to pre-allocate

Returns
healSparseMap – HealSparseMap filled with sentinel values.

Return type
HealSparseMap

classmethod make_empty_like(*sparsemap*, *nside_coverage=None*, *nside_sparse=None*, *dtype=None*, *primary=None*, *sentinel=None*, *wide_mask_maxbits=None*, *metadata=None*, *cov_pixels=None*)

Make an empty map with the same parameters as an existing map.

Parameters

- **sparsemap** (*HealSparseMap*) – Sparse map to use as basis for new empty map.
- **nside_coverage** (*int*, optional) – Coverage nside, default to sparsemap.nside_coverage
- **nside_sparse** (*int*, optional) – Sparse map nside, default to sparsemap.nside_sparse
- **dtype** (*str* or *list* or *np.dtype*, optional) – Datatype, any format accepted by numpy. Default is sparsemap.dtype
- **primary** (*str*, optional) – Primary key for recarray. Default is sparsemap.primary
- **sentinel** (*int* or *float*, optional) – Sentinel value. Default is sparsemap._sentinel
- **wide_mask_maxbits** (*int*, optional) – Create a "wide bit mask" map, with this many bits.
- **metadata** (*dict*-like, optional) – Map metadata that can be stored in FITS header format.
- **cov_pixels** (*np.ndarray* or *list*) – List of integer coverage pixels to pre-allocate

Returns
healSparseMap – HealSparseMap filled with sentinel values.

Return type
HealSparseMap

property metadata

Return the metadata dict.

Returns
metadata

Return type
dict

property n_valid

Get the number of valid pixels in the map.

Returns
n_valid

Return type
int

property nside_coverage

Get the nside of the coverage map

Returns
nside_coverage

Return type
int

property nside_sparse

Get the nside of the sparse map

Returns
nside_sparse

Return type
int

property primary

Get the primary field

Returns
primary

Return type
str

classmethod read(*filename*, *nside_coverage=None*, *pixels=None*, *header=False*, *degrade_nside=None*, *weightfile=None*, *reduction='mean'*, *use_threads=False*)

Read in a HealSparseMap.

Parameters

- **filename** (*str*) – Name of the file to read. May be either a regular HEALPIX map or a HealSparseMap
- **nside_coverage** (*int*, optional) – Nside of coverage map to generate if input file is healpix map.
- **pixels** (*list*, optional) – List of coverage map pixels to read. Only used if input file is a HealSparseMap
- **header** (*bool*, optional) – Return the fits header metadata as well as map? Default is False.
- **degrade_nside** (*int*, optional) – Degrade map to this nside on read. None means leave as-is. Not yet implemented for parquet files.
- **weightfile** (*str*, optional) – Floating-point map to supply weights for degrade wmean. Must be a HealSparseMap (weighted degrade not supported for healpix degrade-on-read). Not yet implemented for parquet files.
- **reduction** (*str*, optional) – Reduction method with degrade-on-read. (mean, median, std, max, min, and, or, sum, prod, wmean). Not yet implemented for parquet files.
- **use_threads** (*bool*, optional) – Use multithreaded reading for parquet files.

Returns

- **healSparseMap** (*HealSparseMap*) – HealSparseMap from file, covered by pixels
- **header** (*fitsio.FITSHDR* or *astropy.io.fits* (if header=True)) – Fits header for the map file.

property sentinel

Get the sentinel of the map.

set_bits_pix(*pixels*, *bits*, *nest=True*)

Set bits of a wide_mask map.

Parameters

- **pixels** (*np.ndarray*) – Integer array of sparse_map pixel values
- **bits** (*list*) – List of bits to set

update_values_pix(*pixels*, *values*, *nest=True*, *operation='replace'*)

Update the values in the sparsemap for a list of pixels. The list of pixels must be unique if the operation is 'replace'.

Parameters

- **pixels** (*np.ndarray*) – Integer array of sparse_map pixel values
- **values** (*np.ndarray* or *None*) – Value or Array of values. Must be same type as sparse_map. If None, then the pixels will be set to the sentinel map value.
- **operation** (*str*, optional) – Operation to use to update values. May be 'replace' (default); 'add'; 'or', or 'and' (for bit masks).

Raises

ValueError – Raised if pixels are not unique and operation is 'replace', or if operation is not 'replace' on a recarray map, or if values is None and operation is not 'replace'.

Notes

During the 'add' operation, if the default sentinel map value is not equal to 0, then any default values will be set to 0 prior to addition.

update_values_pos(*ra_or_theta*, *dec_or_phi*, *values*, *lonlat=True*, *operation='replace'*)

Update the values in the sparsemap for a list of positions.

Parameters

- **ra_or_theta** (*float*, array-like) – Angular coordinates of points on a sphere.
- **dec_or_phi** (*float*, array-like) – Angular coordinates of points on a sphere.
- **values** (*np.ndarray* or *None*) – Value or Array of values. Must be same type as sparse_map. If None, then the pixels will be set to the sentinel map value.
- **lonlat** (*bool*, optional) – If True, input angles are longitude and latitude in degrees. Otherwise, they are co-latitude and longitude in radians.
- **operation** (*str*, optional) – Operation to use to update values. May be 'replace' (default); 'add'; 'or', or 'and' (for bit masks).

Raises

ValueError – If positions do not resolve to unique positions and operation is 'replace', or if values is None and operation is not 'replace'.

Notes

During the 'add' operation, if the default sentinel map value is not equal to 0, then any default values will be set to 0 prior to addition.

upgrade(*nside_out*)

Increase the resolution of the map, i.e., decrease the pixel size.

All covering pixels will be duplicated at the higher resolution.

Parameters

nside_out (*int*) – Output nside resolution parameter.

Returns

healSparseMap – New map, at the desired resolution.

Return type

HealSparseMap

property valid_pixels

Get an array of valid pixels in the sparse map.

Returns
valid_pixels

Return type
np.ndarray

valid_pixels_pos(*lonlat=True*, *return_pixels=False*)

Get an array with the position of valid pixels in the sparse map.

Parameters

- **lonlat** (*bool*, optional) – If True, input angles are longitude and latitude in degrees. Otherwise, they are co-latitude and longitude in radians.
- **return_pixels** (*bool*, optional) – If true, return valid_pixels / co-lat / co-lon or valid_pixels / lat / lon instead of lat / lon

Returns
positions – By default it will return a tuple of the form (*theta*, *phi*) in radians unless *lonlat = True*, for which it will return (*ra*, *dec*) in degrees. If *return_pixels = True*, valid_pixels will be returned as first element in tuple.

Return type
tuple

property wide_mask_maxbits

Get the maximum number of bits stored in the wide mask.

Returns
wide_mask_maxbits – Maximum number of bits. 0 if not wide mask.

Return type
int

property wide_mask_width

Get the width of the wide mask

Returns
wide_mask_width – Width of wide mask array. 0 if not wide mask.

Return type
int

write(*filename*, *clobber=False*, *nocompress=False*, *format='fits'*, *nside_io=4*)

Write a HealSparseMap to a file. Use the *metadata* property from the map to persist additional information in the fits header.

Parameters

- **filename** (*str*) – Name of file to save
- **clobber** (*bool*, optional) – Clobber existing file? Default is False.
- **nocompress** (*bool*, optional) – If this is False, then integer maps will be compressed losslessly. Note that *np.int64* maps cannot be compressed in the FITS standard. This option only applies if format=``fits``.
- **nside_io** (*int*, optional) – The healpix nside to partition the output map files in parquet. Must be less than or equal to nside_coverage, and not greater than 16. This option only applies if format=``parquet``.

- **format** (*str*, optional) – File format. May be `fits`, `parquet`, or `healpix`. Note that the `healpix` EXPLICIT format does not maintain all metadata and coverage information.

Raises

- **NotImplementedError if file format is not supported.** –
- **ValueError if nside_io is out of range.** –

write_moc(*filename*, *clobber=False*)

Write the valid pixels of a HealSparseMap to a multi-order component (MOC) file. Note that values of the pixels are not persisted in MOC format.

Parameters

- **filename** (*str*) – Name of file to save
- **clobber** (*bool*, optional) – Clobber existing file? Default is False.

12.1.2 HealSparseRandoms

healsparse.healSparseRandoms.**make_uniform_randoms**(*sparse_map*, *n_random*, *rng=None*)

Make an array of uniform randoms.

Parameters

- **sparse_map** (*healsparse.HealSparseMap*) – Sparse map object
- **n_random** (*int*) – Number of randoms to generate
- **rng** (*np.random.RandomState*, optional) – Pre-set Random number generator. Default is None.

Returns

- **ra_array** (*np.ndarray*) – Float array of RAs (degrees)
- **dec_array** (*np.ndarray*) – Float array of declinations (degrees)

healsparse.healSparseRandoms.**make_uniform_randoms_fast**(*sparse_map*, *n_random*, *nside_randoms=8388608*, *rng=None*)

Make an array of uniform randoms.

Parameters

- **sparse_map** (*healsparse.HealSparseMap*) – Sparse map object
- **n_random** (*int*) – Number of randoms to generate
- **nside_randoms** (*int*, optional) – Nside for pixel centers to select random points
- **rng** (*np.random.RandomState*, optional) – Pre-set Random number generator. Default is None.

Returns

- **ra_array** (*np.ndarray*) – Float array of RAs (degrees)
- **dec_array** (*np.ndarray*) – Float array of declinations (degrees)

12.1.3 Operations

healsparse.operations.**and_intersection**(*map_list*)

Bitwise or a list of HealSparseMaps as an intersection. Only pixels that are valid in all the input maps will have valid values in the output. Only works on integer maps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to bitwise and

Returns
result – Bitwise and of maps

Return type
HealSparseMap

healsparse.operations.**and_union**(*map_list*)

Bitwise and a list of HealSparseMaps as a union. Empty values will be treated as 0s in the bitwise and, and the output map will have a union of all the input map pixels. Only works in integer maps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to bitwise and

Returns
result – Bitwise and of maps

Return type
HealSparseMap

healsparse.operations.**divide_intersection**(*map_list*, *dtype_out=<class 'numpy.float64'>*)

Divide HealSparseMaps as an intersection. The first map will be used as the starting values, and will be divided by the values in all subsequent maps. Only pixels that are valid in all the input maps will have valid values in the output. This function is equivalent to the python "/" operation.

Parameters

- **map_list** (*list* of *HealSparseMap*) – Input list of maps to take the product
- **dtype_out** (*np.dtype*, optional) – Datatype of output.

Returns
result – map[0] / map[1] / ...

Return type
HealSparseMap

healsparse.operations.**floor_divide_intersection**(*map_list*)

Floor divide HealSparseMaps as an intersection. The first map will be used as the starting values, and will be divided by the values in all subsequent maps. Only pixels that are valid in all the input maps will have valid values in the output. This function is equivalent to the python "//" operation.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to take the product

Returns
result – map[0] / map[1] / ...

Return type
HealSparseMap

healsparse.operations.**max_intersection**(*map_list*)

Element-wise maximum of the intersection of a list of the HealSparseMaps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to compute the maximum of

Returns
result – Element-wise maximum of maps

Return type
HealSparseMap

healsparse.operations.**max_union**(*map_list*)

Element-wise maximum of the union of a list of HealSparseMaps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to compute the maximum of

Returns
result – Element-wise maximum of maps

Return type
HealSparseMap

healsparse.operations.**min_intersection**(*map_list*)

Element-wise minimum of the intersection of a list of HealSparseMaps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to compute the minimum of

Returns
result – Element-wise minimum of maps

Return type
HealSparseMap

healsparse.operations.**min_union**(*map_list*)

Element-wise minimum of the union of a list of HealSparseMaps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to compute the minimum of

Returns
result – Element-wise minimum of maps

Return type
HealSparseMap

healsparse.operations.**or_intersection**(*map_list*)

Bitwise or a list of HealSparseMaps as an intersection. Only pixels that are valid in all the input maps will have valid values in the output. Only works on integer maps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to bitwise or

Returns
result – Bitwise or of maps

Return type
HealSparseMap

healsparse.operations.**or_union**(*map_list*)

Bitwise or a list of HealSparseMaps as a union. Empty values will be treated as 0s in the bitwise or, and the output map will have a union of all the input map pixels. Only works in integer maps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to bitwise or

Returns
result – Bitwise or of maps

Return type
HealSparseMap

healsparse.operations.**product_intersection**(*map_list*)

Compute the product of a list of HealSparseMaps as an intersection. Only pixels that are valid in all the input maps will have valid values in the output.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to take the product

Returns
result – Product of maps

Return type
HealSparseMap

healsparse.operations.**product_union**(*map_list*)

Compute the product of a list of HealSparseMaps as a union. Empty values will be treated as 1s in the product, and the output map will have a union of all the input map pixels.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to take the product

Returns
result – Product of maps

Return type
HealSparseMap

healsparse.operations.**sum_intersection**(*map_list*)

Sum a list of HealSparseMaps as an intersection. Only pixels that are valid in all the input maps will have valid values in the output.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to sum

Returns
result – Summation of maps

Return type
HealSparseMap

healsparse.operations.**sum_union**(*map_list*)

Sum a list of HealSparseMaps as a union. Empty values will be treated as 0s in the summation, and the output map will have a union of all the input map pixels.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to sum

Returns
result – Summation of maps

Return type
HealSparseMap

healsparse.operations.**ufunc_intersection**(*map_list*, *func*, *filler_value=0*)

Apply numpy ufunc to the intersection of a list of HealSparseMaps.

Parameters

- **map_list** (*list* of *HealSparseMap*) – Input list of maps where the operation is applied
- **func** (*np.ufunc*) – Numpy universal function to apply
- **filler_value** (*int* or *float*) – Starting value

Returns
result – Resulting map

Return type
HealSparseMap

healsparse.operations.**ufunc_union**(*map_list*, *func*, *filler_value=0*)

Apply numpy ufunc to the union of a list of HealSparseMaps.

Parameters

- **map_list** (*list* of *HealSparseMaps*) – Input list of maps where the operation is applied
- **func** (*np.ufunc*) – Numpy universal function to apply
- **filler_value** (*int* or *float*) – Starting value and filler for the union

Returns
result – Resulting map

Return type
HealSparseMap

healsparse.operations.**xor_intersection**(*map_list*)

Bitwise xor a list of HealSparseMaps as an intersection. Only pixels that are valid in all the input maps will have valid values in the output. Only works on integer maps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to bitwise xor

Returns
result – Bitwise xor of maps

Return type
HealSparseMap

healsparse.operations.**xor_union**(*map_list*)

Bitwise xor a list of HealSparseMaps as a union. Empty values will be treated as 0s in the bitwise or, and the output map will have a union of all the input map pixels. Only works in integer maps.

Parameters
map_list (*list* of *HealSparseMap*) – Input list of maps to bitwise xor

Returns
result – Bitwise xor of maps

Return type
HealSparseMap

12.1.4 Geometry Library

class healsparse.geom.**Circle**(*, *ra*, *dec*, *radius*, *value*)

Bases: *GeomBase*

Parameters

- **ra** (*float*) – RA in degrees (scalar-only).
- **dec** (*float*) – Declination in degrees (scalar-only).
- **radius** (*float*) – Radius in degrees (scalar-only).
- **value** (*number*) – Value for pixels in the map (scalar or list of bits for *wide_mask*)

__init__(*, *ra*, *dec*, *radius*, *value*)

__repr__()

Return repr(self).

property dec

Get the dec value.

get_pixels(*, *nside*)

Get pixels for this geometric shape.

Parameters
nside (*int*) – HEALPix nside for the pixels.

property ra

Get the RA value.

property radius

Get the radius value.

class healsparse.geom.**Ellipse**(*, *ra*, *dec*, *semi_major*, *semi_minor*, *alpha*, *value*)

Bases: *GeomBase*

Create an ellipse.

Parameters

- **ra** (*float*) – ra in degrees (scalar only)
- **dec** (*float*) – dec in degrees (scalar only)
- **semi_major** (*float*) – The semi-major axis of the ellipse in degrees.
- **semi_minor** (*float*) – The semi-minor axis of the ellipse in degrees.
- **alpha** (*float*) – Inclination angle, counterclockwise with respect to North (degrees).
- **value** (*number*) – Value for pixels in the map (scalar or list of bits for *wide_mask*).

__init__(*, *ra*, *dec*, *semi_major*, *semi_minor*, *alpha*, *value*)

__repr__()

Return repr(self).

property alpha

Get the alpha value.

property dec

Get the dec value.

get_pixels(*, *nside*)

Get pixels for this geometric shape.

Parameters
nside (*int*) – HEALPix nside for the pixels.

property ra

Get the RA value.

property semi_major

Get the semi_major value.

property semi_minor

Get the semi_minor value.

class healsparse.geom.**GeomBase**

Bases: object

Base class for goemetric objects that can convert themselves to maps.

__weakref__

list of weak references to the object (if defined)

get_map(*, *nside_coverage*, *nside_sparse*, *dtype*, *wide_mask_maxbits=None*)

Get a healsparse map corresponding to this geometric primitive.

Parameters

- **nside_coverage** (*int*) – nside of coverage map
- **nside_sparse** (*int*) – nside of sparse map
- **dtype** (*np.dtype*) – dtype of the output array
- **wide_mask_maxbits** (*int*, optional) – Create a "wide bit mask" map, with this many bits.

Returns
hsmap

Return type
healsparse.HealSparseMap

get_map_like(*sparseMap*)

Get a healsparse map corresponding to this geometric primitive, with the same parameters as an input sparseMap.

Parameters
sparseMap (*healsparse.HealSparseMap*) – Input map to match parameters

Returns
hsmap

Return type
healsparse.HealSparseMap

get_pixels(*, *nside*)

Get pixels for this geometric shape.

Parameters
nside (*int*) – HEALPix nside for the pixels.

property is_integer_value

Check if the value is an integer type

property value

Get the value to be used for all pixels in the map.

class healsparse.geom.Polygon(*, *ra*, *dec*, *value*)

Bases: GeomBase

Represent a polygon.

Both counter clockwise and clockwise order for polygon vertices works

Parameters

- **ra** (*np.ndarray* (nvert,)) – RA of vertices in degrees.
- **dec** (*np.ndarray* (nvert,)) – Declination of vertices in degrees.
- **value** (*number*) – Value for pixels in the map

__init__(*, *ra*, *dec*, *value*)

__repr__()

Return repr(self).

property dec

Get the dec values of the vertices.

get_pixels(*, *nside*)

Get pixels for this geometric shape.

Parameters

nside (*int*) – HEALPix nside for the pixels.

property ra

Get the RA values of the vertices.

property vertices

Get the vertices in unit vector form.

healsparse.geom.realize_geom(*geom*, *smap*, *type='or'*)

Realize geometry objects in a map.

Parameters

- **geom** (*Geometric primitive or list thereof*) – List of Geom objects, e.g. Circle, Polygon
- **smap** (*HealSparseMap*) – The map in which to realize the objects.
- **type** (*str*) – Way to combine the list of geometric objects. Default is to "or" them.

12.1.5 HealSparseCoverage

class healsparse.healSparseCoverage.**HealSparseCoverage**(*cov_index_map*, *nside_sparse*)

Bases: object

Class to define a HealSparseCoverage map.

Parameters

- **cov_index_map** (*np.ndarray*) – Coverage map with pixel indices.
- **nside_sparse** (*int*) – Healpix nside of the sparse map.

Returns

cov_map – HealSparseCoverage map.

Return type

HealSparseCoverage

__init__(*cov_index_map*, *nside_sparse*)

__repr__()

Return repr(self).

__str__()

Return str(self).

__weakref__

list of weak references to the object (if defined)

append_pixels(*sparse_map_size*, *new_cov_pix*, *check=True*, *copy=True*)

Append new pixels to the coverage map

Parameters

- **sparse_map_size** (*int*) – Size of current sparse map
- **new_cov_pix** (*np.ndarray*) – Array of new coverage pixels

property bit_shift

Get the bit_shift for the coverage map

Returns

bit_shift – Number of bits to shift from coarse to fine maps

Return type

int

cov_pixels(*sparse_pixels*)

Get coverage pixel numbers (nest) from a set of sparse pixels.

Parameters

sparse_pixels (*np.ndarray*) – Array of sparse pixels

Returns

cov_pixels – Coverage pixel numbers (nest format)

Return type

np.ndarray

`cov_pixels_from_index`(*index*)

Get the coverage pixels from the sparse map index.

Parameters
index (*np.ndarray*) – Array of indices in sparse map

Returns
cov_pixels – Coverage pixel numbers (nest format)

Return type
np.ndarray

`property coverage_mask`

Get the boolean mask of the coverage map.

Returns
cov_mask – Boolean array of coverage mask.

Return type
np.ndarray

`initialize_pixels`(*cov_pix*)

Initialize pixels in the index map

Parameters
cov_pix (*np.ndarray*) – Array of coverage pixels

`classmethod make_empty`(*nside_coverage*, *nside_sparse*)

Make an empty coverage map.

Parameters

- **nside_coverage** (*int*) – Healpix nside for the coverage map
- **nside_sparse** (*int*) – Healpix nside for the sparse map

Returns
healSparseCoverage – HealSparseCoverage from file

Return type
HealSparseCoverage

`classmethod make_from_pixels`(*nside_coverage*, *nside_sparse*, *cov_pixels*)

Make an empty coverage map.

Parameters

- **nside_coverage** (*int*) – Healpix nside for the coverage map
- **nside_sparse** (*int*) – Healpix nside for the sparse map
- **cov_pixels** (*np.ndarray*) – Array of coverage pixels

Returns
healSparseCoverage – HealSparseCoverage from file

Return type
HealSparseCoverage

`property nfine_per_cov`

Get the number of fine (sparse) pixels per coarse (coverage) pixel

Returns
nfine_per_cov – Number of fine (sparse) pixels per coverage pixel

Return type
int

property nside_coverage

Get the nside of the coverage map

Returns
nside_coverage

Return type
int

property nside_sparse

Get the nside of the associated sparse map

Returns
nside_sparse

Return type
int

classmethod read(*filename_or_fits*, *use_threads=False*)

Read in a HealSparseCoverage map from a file.

Parameters

- **coverage_class** (*type*) – Type value of the HealSparseCoverage class.
- **filename_or_fits** (*str* or *HealSparseFits*) – Name of filename or already open *HealSparseFits* object.
- **use_threads** (*bool*, optional) – Use multithreaded reading for parquet files. Should not be necessary for coverage maps.

Returns
cov_map – HealSparseCoverage map from file.

Return type
HealSparseCoverage

12.1.6 Concatenation

healsparse.cat_healsparse_files.**cat_healsparse_files**(*file_list*, *outfile*, *check_overlap=False*, *clobber=False*, *in_memory=False*, *nside_coverage_out=None*, *or_overlap=False*)

Concatenate healsparse files together in a memory-efficient way.

Parameters

- **file_list** (*list* of *str*) – List of filenames to concatenate
- **outfile** (*str*) – Output filename
- **check_overlap** (*bool*, optional) – Check that each file has a unique sparse map. This may be slower.
- **clobber** (*bool*, optional) – Clobber existing outfile
- **in_memory** (*bool*, optional) – Do operations in-memory (required unless fitsio is available).
- **nside_coverage_out** (*int*, optional) – Output map with specific nside_coverage. Default is nside_coverage of first map in file_list.

- **or_overlap** (*bool*, optional) – If True compute the *or* overlap of two integer maps when concatenating.

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