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# **tweakwcs Documentation**

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tweakwcs is a package that provides core algorithms for computing and applying corrections to WCS objects such as to minimize mismatch between image and reference catalogs. Currently only aligning images with FITS WCS and JWST GWCS are supported.



## CONTENT

## 1.1 imalign

A module that provides functions for “aligning” images: specifically, it provides functions for computing corrections to image WCS so that image catalogs “align” to the reference catalog *on the sky*.

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**License**

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```
tweakwcs.imalign.align_wcs(wcscat, refcat=None, ref_tpwcs=None, enforce_user_order=True,
                           expand_refcat=False, minobj=None,
                           match=<tweakwcs.matchutils.XYXYMatch object>, fitgeom='general',
                           nclip=3, sigma=(3.0, 'rmse'), clip_accum=False,
                           group_bb_policy='auto')
```

Align (groups of) image catalogs by adjusting the parameters of their WCS based on fits between matched sources in these catalogs and a reference catalog which may be automatically created from one of the input `wcscat` catalogs.

**Warning:** This function modifies the `wcs` attribute of each item in the input `wcscat` list!

Upon completion, this function will add a field `'fit_info'` to the `meta` attribute of the input WCS correctors (except of the one chosen as a reference catalog when `refcat` is `None` (<https://docs.python.org/3/library/constants.html#None>)) containing a dictionary describing matching and fit results. For a description of the items in this dictionary, see [tweakwcs.wcsimage.WCSGroupCatalog.align\\_to\\_ref\(\)](#). In addition to the status set by [align\\_to\\_ref\(\)](#), this function may set status to `'REFERENCE'` for an input image used as a reference image when a reference catalog is not provided. In this case no other fields in the `'fit_info'` will be present because a reference image is not being aligned. When alignment failed, the reason for failure is provided after alignment status.

**Warning:** Unless status in 'fit\_info' is 'SUCCESS', there is no guarantee that other fields in 'fit\_info' are present or valid. Therefore, it is advisable verify that status is 'SUCCESS' before attempting to access other items, for example:

```
>>> fit_info = wscat[0].meta.get('fit_info') # noqa
>>> if fit_info['status'] == 'SUCCESS':
...     print("shifts: [{}, {}]" .format(*fit_info['shift']))
... else:
...     print("tweak info not available for this image")
```

## Parameters

**wscat:** `tweakwcs.correctors.WCSCorrector`, list of `tweakwcs.correctors.WCSCorrector`

A list of all `WCSCorrector`-derived WCS correctors whose meta dictionary **must** contain 'catalog' item with a non-empty table value of type `astropy.table.Table` (<https://docs.astropy.org/en/stable/api/astropy.table.Table.html#astropy.table.Table>). This catalog must contain 'x' and 'y' columns which indicate source coordinates (in pixels) in the associated image. An optional column in the catalog is the 'weight' column, which when present, will be used in fitting. See Notes section for further details. In addition to 'catalog', the following items in the meta dictionary are recognized/supported: 'name' and 'group\_id'. 'name' is catalog's name and it used to identify catalog during logging. If 'name' value is `None` (<https://docs.python.org/3/library/constants.html#None>) or not present at all in the meta of a catalog, the name of that catalog will reported as 'Unknown'. Group ID that may be used for identifying catalogs that need to be aligned together. `group_id` must be hashable. If 'group\_id' is `None` (<https://docs.python.org/3/library/constants.html#None>) or not provided, each input WCS/catalog will be aligned individually.

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**Note:** Upon completion this function will add 'fit\_info' item (a dictionary) to input object's meta dictionary. See **Notes** section for more details.

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**Warning:** This function modifies the WCS of `WCSCorrector` objects by calling their `set_correction()` method.

**refcat:** `astropy.table.Table`, optional

A reference source catalog. The catalog must contain 'RA' and 'DEC' columns which indicate reference source world coordinates (in degrees). An optional column in the catalog is the 'weight' column, which when present, will be used in fitting. See Notes section for further details.

**ref\_tpwcs:** `WCSCorrector`, `None`, optional

A reference WCS of the type `WCSCorrector` that provides the tangent plane in



which matching will be performed and corrections will be defined. When not provided (i.e., set to `None` (<https://docs.python.org/3/library/constants.html#None>)), reference tangent plane will be defined from the first `WCSCorrector` object *in the re-ordered* (if `enforce_user_order` was set to `True` (<https://docs.python.org/3/library/constants.html#True>)) input list `wscat`.

**enforce\_user\_order: bool, optional**

Specifies whether images should be aligned in the order specified in the file input parameter or `align` should optimize the order of alignment by intersection area of the images. Default value (`True` (<https://docs.python.org/3/library/constants.html#True>)) will align images in the user specified order, except when some images cannot be aligned in which case `align` will optimize the image alignment order. Alignment order optimization is available *only* when `expand_refcat` is `True` (<https://docs.python.org/3/library/constants.html#True>).

**expand\_refcat: bool, optional**

Specifies whether to add new sources from just matched images to the reference catalog to allow next image to be matched against an expanded reference catalog. By default, the reference catalog is not being expanded.

If `refcat` is not `None` (<https://docs.python.org/3/library/constants.html#None>) and contains an 'id' column, then sources being added to the reference catalog will be assigned consecutive IDs that continue maximum ID in the `refcat`.

If one desires to uniquely associate source in the expanded catalog to their original catalogs, it is recommended that one assign unique IDs to all sources in all input catalogs **and** in the reference catalog in a separate column such as 'uuid'.

**minobj: int, None, optional**

Minimum number of identified objects from each input image to use in matching objects from other images. If the default `None` (<https://docs.python.org/3/library/constants.html#None>) value is used then `align` will automatically determine the minimum number of sources from the value of the `fitgeom` parameter.

**match: MatchCatalogs, function, None, optional**

A callable that takes two arguments: a reference catalog and an image catalog. Both catalogs will have columns 'TPx' and 'TPy' that represent the source coordinates in some common (to both catalogs) coordinate system.

**fitgeom: {'shift', 'rshift', 'rscale', 'general'}, optional**

The fitting geometry to be used in fitting the matched object lists. This parameter is used in fitting the offsets, rotations and/or scale changes from the matched object lists. The 'general' fit geometry allows for independent scale and rotation for each axis.

**nclip: int, None, optional**

Number (a non-negative integer) of clipping iterations in fit. Clipping will be turned off if `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**sigma: float, tuple of the form (float, str), optional**

When a tuple is provided, first value (a positive number) indicates the number of “fit error estimates” to use for clipping. The second value (a string) indicates the statistic to be used for “fit error estimate”. Currently the following values are supported: 'rmse', 'mae', and 'std' - see [iter\\_linear\\_fit](#) for more details.

When sigma is a single number, it must be a positive number and the default error estimate 'rmse' is assumed.

This parameter is ignored when nclip is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**clip\_accum: bool, optional**

Indicates whether or not to reset the list of “bad” (clipped out) sources after each clipping iteration. When set to `True` (<https://docs.python.org/3/library/constants.html#True>) the list only grows with each iteration as “bad” positions never re-enter the pool of available position for the fit. By default the list of “bad” source positions is purged at each iteration. This parameter is ignored when nclip is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**group\_bb\_policy: int, {'exact', 'auto'}**

Describes how to compute the bounding polygon of the group. 'exact' will compute the exact union of bounding boxes of input images. An integer number will *approximate* the bounding box using convex hull if the number of input images is exceeds the value of group\_bb\_policy and it will switch to exact computations (using unions) otherwise. 'auto' is the same as setting threshold to 50.

**Returns****eff\_refcat: astropy.table.Table**

Effective reference catalog used for aligning all images. Depending on the values of the input parameters `refcat`, `enforce_user_order`, and `expand_refcat`, effective reference catalog may be one of the input image catalogs, the original `refcat` catalog, an expanded `refcat` with a combination of source positions from all input images.

**Notes****1. Weights:**

When fitting image sources to reference catalog sources, we can specify which sources have higher weights. This can be done by assigning a “weight” to each source by specifying these values in the optional 'weight' column of either the reference catalog, image catalog, or both.

When weights are not provided, all sources are weighed equally. When only either image or reference catalog weights are provided, the sources will be weighted with the specified weights. When *both* image *and* reference catalogs specify weights for the same sources, the two weights will be combined into a single weight as:

$$1/w = 1/w_i + 1/w_r$$

**Warning:** Keep in mind that when a group catalog is created from individual catalogs, weights of the group catalog are created by *concatenating* weights of individual catalogs. Therefore, for the weighting of groups of catalogs to work correctly, the weights of individual catalogs should be scaled in such a way that when individual catalogs are combined into a single “group catalog”, weights preserve their relative values.

For example, let’s say a group is formed from two individual catalogs. Let’s say first catalog contains four sources with equal weights  $[1, 1, 1, 1]$  and the second catalog contains two sources with weights  $[1, 1]$  then the group’s catalogs sources will also have equal weights  $[1, 1, 1, 1, 1, 1]$ . However, if each individual catalog’s weights were normalized such that sum of all weights is 1, then group’s sources will be weighed unequally:  $[0.25, 0.25, 0.25, 0.25, 0.5, 0.5]$ .

**Warning:** When image catalogs contain optional 'weight' column, then all image catalogs in a group must contain this column.

## 2. 'fit\_info':

Upon completion, this function will add 'fit\_info' item (itself a dictionary) to input object’s meta dictionary. If input objects are *WCSCorrector* WCS correctors, then `WCSCorrector.meta['fit_info']` will be set to a dictionary containing fit information.

**Note:** For *WCSCorrector* that are aligned in a group, the 'matrix' and 'shift' items in the 'fit\_info' dictionary may differ from the values of the same items in `WCSCorrector.meta` dictionary. This is normal since WCS corrections (in *WCSCorrector*) are applied in the image’s WCS plane while fit may be performed in a slightly different tangent plane.

```
tweakwcs.imalign.fit_wcs(refcat, imcat, corrector, ref_tpwcs=None, fitgeom='general', nclip=3,
                        sigma=(3.0, 'rmse'), clip_accum=False, group_bb_policy='auto')
```

“Tweak” a **single** image’s WCS by fitting image catalog to a reference catalog. This is a simplified version of *align\_wcs* that does not perform matching and is limited to the fitting part.

**Note:** Both reference and image catalogs must have been **matched** *prior to* calling `fit_wcs()`. This means that the lengths of both `refcat` and `imcat` catalogs must be equal *and* that coordinates with the same indices in both catalogs correspond to the same source.

**Warning:** If `corrector.meta` dictionary contains 'catalog' keyword, it will be ignored.

## Parameters

**refcat:** `astropy.table.Table`

A reference source catalog. The catalog must contain 'RA' and 'DEC' columns

which indicate reference source world coordinates (in degrees). An optional column in the catalog is the 'weight' column, which when present, will be used in fitting. See `Notes` section for further details.

**imcat: `astropy.table.Table`**

Source catalog associated with an image whose WCS needs to be aligned by fitting a linear transformation to `imcat` source positions so as to align them to the same sources from the `refcat` catalog. Must contain 'x' and 'y' columns which indicate source coordinates (in pixels) in the associated image. An optional column in the catalog is the 'weight' column, which when present, will be used in fitting. See `Notes` section for further details.

**corrector: `WCSCorrector`**

A WCS associated with the image from which the catalog was derived. This `WCSCorrector`-subclassed WCS corrector object must also define a tangent plane that will be used for fitting the two catalogs' sources and in which WCS corrections will be applied.

**ref\_tpwcs: `WCSCorrector`, `None`, optional**

A reference WCS of the type `WCSCorrector` that provides the tangent plane in which matching will be performed and corrections will be defined. When not provided (i.e., set to `None` (<https://docs.python.org/3/library/constants.html#None>)), reference tangent plane will be the same as defined by `corrector` argument.

**fitgeom: {'shift', 'rshift', 'rscale', 'general'}, optional**

The fitting geometry to be used in fitting the matched object lists. This parameter is used in fitting the offsets, rotations and/or scale changes from the matched object lists. The 'general' fit geometry allows for independent scale and rotation for each axis.

**nclip: `int`, `None`, optional**

Number (a non-negative integer) of clipping iterations in fit. Clipping will be turned off if `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**sigma: `float`, tuple of the form (`float`, `str`), optional**

When a tuple is provided, first value (a positive number) indicates the number of "fit error estimates" to use for clipping. The second value (a string) indicates the statistic to be used for "fit error estimate". Currently the following values are supported: 'rmse', 'mae', and 'std' - see [iter\\_linear\\_fit](#) for more details.

When `sigma` is a single number, it must be a positive number and the default error estimate 'rmse' is assumed.

This parameter is ignored when `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**clip\_accum: `bool`, optional**

Indicates whether or not to reset the list of "bad" (clipped out) sources after each clipping iteration. When set to `True` (<https://docs.python.org/3/library/constants.html#True>) the list only grows with each iteration as "bad" positions never re-enter the pool of available

position for the fit. By default the list of “bad” source positions is purged at each iteration. This parameter is ignored when `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**group\_bb\_policy:** int, {'exact', 'auto'}

Describes how to compute the bounding polygon of the group. 'exact' will compute the exact union of bounding boxes of input images. An integer number will *approximate* the bounding box using convex hull if the number of input images exceeds the value of `group_bb_policy` and it will switch to exact computations (using unions) otherwise. 'auto' is the same as setting threshold to 50.

## Returns

**twwcs:** WCSCorrector

“Tweaked” (aligned) WCS that contains tangent-plane corrections so that reference and image catalog sources better align in the tangent plane and therefore on the sky as well.

## Notes

When fitting image sources to reference catalog sources, we can specify which sources have higher weights. This can be done by assigning a “weight” to each source by specifying these values in the optional 'weight' column of either the reference catalog, image catalog, or both.

When weights are not provided, all sources are weighed equally. When only either image or reference catalog weights are provided, the sources will be weighted with the specified weights. When *both* image *and* reference catalogs specify weights for the same sources, the two weights will be combined into a single weight as:

$$1/w = 1/w_i + 1/w_r$$

**Warning:** Keep in mind that when a group catalog is created from individual catalogs, weights of the group catalog are created by *concatenating* weights of individual catalogs. Therefore, for the weighting of groups of catalogs to work correctly, the weights of individual catalogs should be scaled in such a way that when individual catalogs are combined into a single “group catalog”, weights preserve their relative values.

For example, let’s say a group is formed from two individual catalogs. Let’s say first catalog contains four sources with equal weights [1, 1, 1, 1] and the second catalog contains two sources with weights [1, 1] then the group’s catalogs sources will also have equal weights [1, 1, 1, 1, 1, 1]. However, if each individual catalog’s weights were normalized such that sum of all weights is 1, then group’s sources will be weighed unequally: [0.25, 0.25, 0.25, 0.25, 0.5, 0.5].

Upon **successful** completion, this function will set the 'fit\_info' key value of the meta attribute of the returned WCSCorrector object. 'fit\_info' is a dictionary with the following items:

- **‘shift’:** A `numpy.ndarray` with two components of the computed shift. Note: shift is in units of the *tangent plane*.

- **‘matrix’**: A 2x2 `numpy.ndarray` with the computed generalized rotation matrix.
- **‘proper\_rot’**: Rotation angle (degree) as if the rotation is proper.
- **‘rot’**: A tuple of (`rotx`, `roty`) - the rotation angles with regard to the X and Y axes.
- **‘<rot>’**: *Arithmetic mean* of the angles of rotation around X and Y axes.
- **‘scale’**: A tuple of (`sx`, `sy`) - scale change in the direction of the X and Y axes.
- **‘<scale>’**: *Geometric mean* of scales `sx` and `sy`.
- **‘skew’**: Computed skew.
- **‘proper’**: a boolean indicating whether the rotation is proper.
- **‘fitgeom’**: Fit geometry (allowed transformations) used for fitting data (to minimize residuals). This is copy of the input argument `fitgeom`.
- **‘center’**: Center of rotation in the *tangent plane* of the computed linear transformations.
- **‘fitmask’**: A boolean array indicating which source positions where used for fitting (`True` (<https://docs.python.org/3/library/constants.html#True>)) and which were clipped out (`False` (<https://docs.python.org/3/library/constants.html#False>)). **NOTE:** For weighted fits, positions with zero weights are automatically excluded from the fits.
- **‘eff\_nclip’**: Effective number of clipping iterations
- **‘rmse’**: fit Root-Mean-Square Error in *tangent plane* coordinates of corrected image source positions from reference source positions.
- **‘mae’**: fit Mean Absolute Error in *tangent plane* coordinates of corrected image source positions from reference source positions.
- **‘std’**: Norm of the standard deviation of the residuals in *tangent plane* along each axis.
- **‘resids’**: An array of residuals of the fit in the *tangent plane*.

**NOTE:** Only the residuals for the “valid” points are reported here. Therefore the length of this array may be smaller than the length of input arrays of positions.
- **‘fit\_RA’**: first (corrected) world coordinate of input source positions used in fitting.
- **‘fit\_DEC’**: second (corrected) world coordinate of input source positions used in fitting.
- **‘status’**: Alignment status. Currently two possible status are possible 'SUCCESS' or 'FAILED: reason for failure'. When alignment failed, the reason for failure is provided after alignment status.

## 1.2 WCS Correctors

This module provides support for manipulating tangent-plane corrections of WCS.

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### License

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**class** `tweakwcs.correctors.FITSWCSCorrector`(*wcs*, *meta=None*)

A class for holding FITS WCS information and for managing tangent-plane corrections. The units of the tangent plane of this corrector are same as detector coordinates.

---

**Note:** Currently only WCS objects that have CPDIS, DET2IM, and SIP distortions *before* the application of the CD or PC matrix are supported.

---

### Parameters

**wcs:** `astropy.wcs.WCS`

An `astropy.wcs.WCS` (<https://docs.astropy.org/en/stable/api/astropy.wcs.WCS.html#astropy.wcs.WCS>) object.

### property `bounding_box`

Get the bounding box (if any) of the underlying image for which the original WCS is defined.

### `det_to_tanp`(*x*, *y*)

Convert detector (pixel) coordinates to tangent plane coordinates.

### `det_to_world`(*x*, *y*)

Convert pixel coordinates to sky coordinates using full (i.e., including distortions) transformations.

**set\_correction**(*matrix=[[1, 0], [0, 1]]*, *shift=[0, 0]*, *ref\_tpwcs=None*, *meta=None*, *\*\*kwargs*)

Computes a corrected (aligned) wcs based on the provided linear transformation. In addition, this function updates the *meta* attribute of the `FITSWCSCorrector` object with the the values of keyword arguments except for the argument *meta* which is *merged* with the *attribute meta*.

### Parameters

**matrix:** `list`, `numpy.ndarray`

A 2x2 array or list of lists coefficients representing scale, rotation, and/or skew transformations.

**shift:** `list`, `numpy.ndarray`

A list of two coordinate shifts to be applied to coordinates *after* *matrix* transformations are applied.

**ref\_tpwcs:** `WCSCorrector`, `None`, `optional`

A reference WCS of the type `WCSCorrector` that provides the tangent plane

in which corrections (`matrix` and `shift`) were defined. When not provided (i.e., set to `None` (<https://docs.python.org/3/library/constants.html#None>)), it is assumed that the transformations are being applied directly to *this* image WCS' tangent plane.

**meta:** dict, None, optional

Dictionary that will be merged to the object's `meta` fields.

**\*\*kwargs:** optional parameters

Optional parameters for the WCS corrector. *FITSWCSCorrector* ignores these arguments (except for storing them in the `meta` attribute).

**tanp\_to\_det**(*x*, *y*)

Convert tangent plane coordinates to detector (pixel) coordinates.

**tanp\_to\_world**(*x*, *y*)

Convert tangent plane coordinates to world coordinates.

**units** = 'pixel'

**world\_to\_det**(*ra*, *dec*)

Convert sky coordinates to image's pixel coordinates using full (i.e., including distortions) transformations.

**world\_to\_tanp**(*ra*, *dec*)

Convert tangent plane coordinates to detector (pixel) coordinates.

**class** `tweakwcs.correctors.JWSTWCSCorrector`(*wcs*, *wcsinfo*, *meta=None*)

A class for holding JWST gWCS information and for managing tangent-plane corrections. The units of the tangent plane of this corrector are arcsec and the axes are not along parallel to the axes of the detector's coordinate system.

### Parameters

**wcs:** GWCS

A GWCS object.

**wcsinfo:** dict

A dictionary containing reference angles of JWST instrument provided in the `wcsinfo` property of JWST meta data.

This dictionary **must contain** the following keys and values:

**'v2\_ref': float**

V2 position of the reference point in arc seconds.

**'v3\_ref': float**

V3 position of the reference point in arc seconds.

**'roll\_ref': float**

Roll angle in degrees.

**meta:** dict, None, optional

Dictionary that will be merged to the object's `meta` fields.



**property bounding\_box**

Get the bounding box (if any) of the underlying image for which the original WCS is defined.

**det\_to\_tanp**(*x*, *y*)

Convert detector (pixel) coordinates to tangent plane coordinates.

**det\_to\_world**(*x*, *y*)

Convert pixel coordinates to sky coordinates using full (i.e., including distortions) transformations.

**property ref\_angles**

Return a wcsinfo-like dictionary of main WCS parameters.

**set\_correction**(*matrix*=[[1, 0], [0, 1]], *shift*=[0, 0], *ref\_tpwcs*=None, *meta*=None, **\*\*kwargs**)

Sets a tangent-plane correction of the GWCS object according to the provided linear parameters. In addition, this function updates the meta attribute of the *JWSTWCSCorrector* object with the values of keyword arguments except for the argument meta which is *merged* with the attribute meta.

**Parameters****matrix: list, numpy.ndarray**

A 2x2 array or list of lists coefficients representing scale, rotation, and/or skew transformations.

**shift: list, numpy.ndarray**

A list of two coordinate shifts to be applied to coordinates *after* matrix transformations are applied.

**ref\_tpwcs: WCSCorrector, None, optional**

A reference WCS of the type *WCSCorrector* that provides the tangent plane in which corrections (*matrix* and *shift*) were defined. When not provided (i.e., set to *None* (<https://docs.python.org/3/library/constants.html#None>)), it is assumed that the transformations are being applied directly to *this* image WCS' tangent plane.

**meta: dict, None, optional**

Dictionary that will be merged to the object's meta fields.

**\*\*kwargs: optional parameters**

Optional parameters for the WCS corrector. *JWSTWCSCorrector* ignores these arguments (except for storing them in the meta attribute).

**tanp\_to\_det**(*x*, *y*)

Convert tangent plane coordinates to detector (pixel) coordinates.

**tanp\_to\_world**(*x*, *y*)

Convert tangent plane coordinates to world coordinates.

**units = 'arcsec'**

**world\_to\_det**(*ra*, *dec*)

Convert sky coordinates to image's pixel coordinates using full (i.e., including distortions) transformations.

**world\_to\_tanp**(*ra*, *dec*)

Convert tangent plane coordinates to detector (pixel) coordinates.

**class** tweakwcs.correctors.**WCSCorrector**(*wcs*, *meta=None*)

A class that provides common interface for manipulating WCS information and for managing tangent-plane corrections.

#### Parameters

**wcs:** ``WCS object``

A WCS object supported by a child class.

**meta:** dict, None, optional

Dictionary that will be merged to the object's meta fields.

**property** bounding\_box

Get the bounding box (if any) of the underlying image for which the original WCS is defined.

**copy**()

Returns a deep copy of this object.

**abstract** det\_to\_tanp(*x*, *y*)

Convert detector (pixel) coordinates to tangent plane coordinates.

**abstract** det\_to\_world(*x*, *y*)

Convert pixel coordinates to sky coordinates using full (i.e., including distortions) transformations.

**property** meta

**property** original\_wcs

Get original WCS object.

**abstract** set\_correction(*matrix=[[1, 0], [0, 1]]*, *shift=[0, 0]*, *ref\_tpwcs=None*, *meta=None*, *\*\*kwargs*)

Sets a tangent-plane correction of the WCS object according to the provided linear parameters. In addition, this function updates the meta attribute of the *WCSCorrector*-derived object with the values of keyword arguments except for the argument meta which is *merged* with the *attribute* meta.

#### Parameters

**matrix:** list, numpy.ndarray, optional

A 2x2 array or list of lists coefficients representing scale, rotation, and/or skew transformations.

**shift:** list, numpy.ndarray, optional

A list of two coordinate shifts to be applied to coordinates *after* matrix transformations are applied.

**ref\_tpwcs:** WCSCorrector, None, optional

A reference WCS of the type `WCSCorrector` that provides the tangent plane in which corrections (`matrix` and `shift`) were defined. When not provided (i.e., set to `None` (<https://docs.python.org/3/library/constants.html#None>)), it is assumed that the transformations are being applied directly to *this* image WCS' tangent plane.

**meta:** dict, None, optional

Dictionary that will be merged to the object's meta fields.

**\*\*kwargs:** optional parameters

Optional parameters for the WCS corrector.

**property** `tanp_center_pixel_scale`

Estimate pixel scale in the tangent plane near a location in the detector's coordinate system corresponding to the origin of the tangent plane.

**Returns**

**pscale:** float

Pixel scale [in units used in the tangent plane coordinate system] in the tangent plane near a location in the detector's plane corresponding to the origin of the tangent plane.

**tanp\_pixel\_scale**(*x*, *y*)

Estimate pixel scale in the tangent plane near a location in the detector's coordinate system given by parameters *x* and *y*.

**Parameters**

**x:** int, float

X-coordinate of the pixel in the detector's coordinate system near which pixel scale in the tangent plane needs to be estimated.

**y:** int, float

Y-coordinate of the pixel in the detector's coordinate system near which pixel scale in the tangent plane needs to be estimated.

**Returns**

**pscale:** float

Pixel scale [in units used in the tangent plane coordinate system] in the tangent plane near a location specified by detector coordinates *x* and *y*.

**abstract** `tanp_to_det`(*x*, *y*)

Convert tangent plane coordinates to detector (pixel) coordinates.

**abstract** `tanp_to_world`(*x*, *y*)

Convert tangent plane coordinates to world coordinates.

**units** = None

**property** `wcs`

Get current WCS object.

**abstract world\_to\_det**(*ra*, *dec*)

Convert sky coordinates to image's pixel coordinates using full (i.e., including distortions) transformations.

**abstract world\_to\_tanp**(*ra*, *dec*)

Convert tangent plane coordinates to detector (pixel) coordinates.

## 1.3 matchutils

A module that provides algorithms matching catalogs and for initial estimation of shifts based on 2D histograms.

### License

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**class** tweakwcs.matchutils.**MatchCatalogs**

A class that provides common interface for matching catalogs.

**class** tweakwcs.matchutils.**XYXYMatch**(*searchrad=3.0*, *separation=0.5*, *use2dhist=True*,  
*xoffset=0.0*, *yoffset=0.0*, *tolerance=1.0*)

Catalog source matching in tangent plane. Uses `xyxymatch` algorithm to cross-match sources between this catalog and a reference catalog.

---

**Note:** The tangent plane is a plane tangent to the celestial sphere and it must be not distorted, that is, if *image* coordinates are distorted, then distortion correction must be applied to them before tangent plane coordinates are computed. Alternatively, one can think that undistorted world coordinates are projected from the sphere onto the tangent plane.

---

### Parameters

**searchrad: float, optional**

The search radius for a match (in units of the tangent plane).

**separation: float, optional**

The minimum separation in the tangent plane (in units of the tangent plane) for sources in the image and reference catalogs in order to be considered to be distinct sources. Objects closer together than `separation` distance are removed from the image and reference coordinate catalogs prior to matching. This parameter gets passed directly to `xyxymatch()` for use in matching the object lists from each image with the reference catalog's object list.

**use2dhist: bool, optional**

Use 2D histogram to find initial offset?

**xoffset: float, optional**

Initial estimate for the offset in X (in units of the tangent plane) between the sources in the image and the reference catalogs. This offset will be used for

all input images provided. This parameter is ignored when `use2dhist` is `True` (<https://docs.python.org/3/library/constants.html#True>).

**yoffset: float, optional**

Initial estimate for the offset in Y (in units of the tangent plane) between the sources in the image and the reference catalogs. This offset will be used for all input images provided. This parameter is ignored when `use2dhist` is `True` (<https://docs.python.org/3/library/constants.html#True>).

**tolerance: float, optional**

The matching tolerance (in units of the tangent plane) after applying an initial solution derived from the ‘triangles’ algorithm. This parameter gets passed directly to `xyxymatch()` for use in matching the object lists from each image with the reference image’s object list.

## 1.4 wcsimage

This module provides support for working with image footprints on the sky and source catalogs.

**Authors**

Mihai Cara

**License**

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**class** `tweakwcs.wcsimage.RefCatalog`(*catalog*, *name=None*, *footprint\_tol=1.0*)

An object that holds a reference catalog and provides tools for coordinate conversions using reference WCS as well as catalog manipulation and expansion.

**Parameters**

**catalog: astropy.table.Table**

Reference catalog.

---

**Note:** Reference catalogs (`Table` (<https://docs.astropy.org/en/stable/api/astropy.table.Table.html#astropy.table.Table>) must contain *both* 'RA' and 'DEC' columns.

---

**name: str, None, optional**

Name of the reference catalog.

**footprint\_tol: float, optional**

Matching tolerance in arcsec. This is used to estimate catalog’s footprint when catalog contains only one or two sources.

**calc\_bounding\_polygon()**

Calculate bounding polygon of the sources in the catalog.

**calc\_tanp\_xy**(*tanplane\_wcs*)

Compute x- and y-positions of the sources from the reference catalog in the tangent plane provided by the *tanplane\_wcs*. This creates the following columns in the catalog's table: 'TPx' and 'TPy'.

**Parameters****tanplane\_wcs: WCSCorrector**

A *WCSCorrector* object that will provide transformations to the tangent plane to which sources of this catalog should be “projected”.

**property catalog**

Get/set image's catalog.

**expand\_catalog**(*catalog*)

Expand current reference catalog with sources from another catalog.

If current catalog is empty, then the catalog being added will become the new reference catalog. In this case if the *catalog* does have *id* column, those ID values will be preserved. If the *catalog* does not contain an ID column, then the new IDs will be assigned in increasing order starting with 1.

If the existing reference catalog is not empty, then the IDs from the *catalog* being added will be discarded and new IDs will be assigned in the increasing order such as to continue the numbering of existing source positions in the reference catalog.

**Parameters****catalog: astropy.table.Table**

A catalog of new sources to be added to the existing reference catalog. *catalog* must contain both 'RA' and 'DEC' columns.

**intersection**(*wcsim*)

Compute intersection of this *WCSImageCatalog* object and another *WCSImageCatalog*, *WCSGroupCatalog*, *RefCatalog*, or *SphericalPolygon* object.

**Parameters****wcsim: WCSImageCatalog, WCSGroupCatalog, RefCatalog, SphericalPolygon**

Another object that should be intersected with this *WCSImageCatalog*.

**Returns****polygon: SphericalPolygon**

A *SphericalPolygon* that is the intersection of this *WCSImageCatalog* and *wcsim*.

**intersection\_area**(*wcsim*)

Calculate the area of the intersection polygon.

**property name**

Get/set *RefCatalog* object's name.

**property poly\_area**

Area of the bounding polygon (in srاد).

**property polygon**

Get image's (or catalog's) bounding spherical polygon.

**class** tweakwcs.wcsimage.WCSGroupCatalog(*images*, *name=None*, *bb\_policy='auto'*)

A class that holds together *WCSTImageCatalog* image catalog objects whose relative positions are fixed and whose source catalogs should be fitted together to a reference catalog.

**Parameters****images: list of WCSTImageCatalog**

A list of *WCSTImageCatalog* image catalogs.

**name: str, None, optional**

Name of the group.

**bb\_policy: int, {'exact', 'auto'}**

Describes how to compute the bounding polygon of the group. 'exact' will compute the exact union of bounding boxes of input *images*. An integer number will *approximate* the bounding box using convex hull if the number of input *images* is exceeds the value of *bb\_policy* and it will switch to exact computations (using unions) otherwise. 'auto' is the same as setting threshold to 50.

**align\_to\_ref**(*refcat*, *ref\_tpwcs=None*, *match=None*, *minobj=None*, *fitgeom='rscale'*, *nclip=3*, *sigma=(3.0, 'rmse')*, *clip\_accum=False*)

Matches sources from the image catalog to the sources in the reference catalog, finds the affine transformation between matched sources, and adjusts images' WCS according to this fit.

Upon successful return, this function will also set the following fields of the *fit\_info* attribute of each member *WCSTImageCatalog* object:

- **'fitgeom'**: the value of the *fitgeom* argument
- **'eff\_minobj'**: effective value of the *minobj* parameter
- **'matrix'**: computed rotation matrix
- **'shift'**: shift (offset) along X- and Y-axis in units of the *tangent plane* coordinates.
- **'rot'**: A tuple of (*rotx*, *roty*) - the rotation angles with regard to the X and Y axes.
- **'<rot>'**: *Arithmetic mean* of the angles of rotation around X and Y axes.
- **'proper\_rot'**: rotation angle as if rotation is a proper rotation.
- **'proper'**: Indicates whether the rotation is a proper rotation (boolean)
- **'scale'**: A tuple of (*sx*, *sy*) - scale change in the direction of the X and Y axes.
- **'<scale>'**: *Geometric mean* of scales *sx* and *sy*.
- **'skew'**: Computed skew - an angle in the range [-180, 180).
- **'center'**: Center of rotation in the *tangent plane* of the computed linear transformations.

- **‘fitmask’**: boolean array indicating (with [True](https://docs.python.org/3/library/constants.html#True) (<https://docs.python.org/3/library/constants.html#True>)) sources **used** for fitting
- **‘nmatches’** [when `match` is not [None](https://docs.python.org/3/library/constants.html#None) (<https://docs.python.org/3/library/constants.html#None>)]: number of matched sources
- **‘matched\_ref\_idx’** [when `match` is not [None](https://docs.python.org/3/library/constants.html#None) (<https://docs.python.org/3/library/constants.html#None>)]: indices of the matched sources in the reference catalog
- **‘matched\_input\_idx’** [when `match` is not [None](https://docs.python.org/3/library/constants.html#None) (<https://docs.python.org/3/library/constants.html#None>)]: indices of the matched sources in the “input” catalog (the catalog from image to be aligned)
- **‘fit\_ref\_idx’**: indices of the sources from the reference catalog used for fitting (a subset of ‘matched\_ref\_idx’ indices, when `match` is not [None](https://docs.python.org/3/library/constants.html#None) (<https://docs.python.org/3/library/constants.html#None>), left after clipping iterations performed during fitting)
- **‘fit\_input\_idx’**: indices of the sources from the “input” (image) catalog used for fitting (a subset of ‘matched\_input\_idx’ indices, when `match` is not [None](https://docs.python.org/3/library/constants.html#None) (<https://docs.python.org/3/library/constants.html#None>), left after clipping iterations performed during fitting)
- **‘rmse’**: fit Root-Mean-Square Error in *tangent plane* coordinates of corrected image source positions from reference source positions.
- **‘mae’**: fit Mean Absolute Error in *tangent plane* coordinates of corrected image source positions from reference source positions.
- **‘std’**: Norm of the STandard Deviation of the residuals in *tangent plane* along each axis.
- **‘fit\_RA’**: first (corrected) world coordinate of input source positions used in fitting.
- **‘fit\_DEC’**: second (corrected) world coordinate of input source positions used in fitting.
- **‘status’**: Alignment status. Currently two possible status are possible 'SUCCESS' or 'FAILED: reason for failure'. When alignment failed, the reason for failure is provided after alignment status.

---

**Note:** A 'SUCCESS' status does not indicate a “good” alignment. It simply indicates that alignment algorithm has completed without errors. Use other fields to evaluate alignment: fit RMSE and MAE values, number of matched sources, etc.

---

---

**Note:** Many quantities in `fit_info` are in units of the *tangent plane* coordinates, e.g., `shift`, `rmse`, `std`, `mae`. See specific WCSCorrector in [correctors](#) for the units of the tangent plane.

---

## Parameters

### refcat: RefCatalog

A [RefCatalog](#) object that contains a catalog of reference sources.



**ref\_tpwcs: WCSCorrector**

A `WCSCorrector` object that defines a projection tangent plane to be used for matching and fitting during alignment.

**match: MatchCatalogs, function, None, optional**

A callable that takes two arguments: a reference catalog and an image catalog.

**minobj: int, None, optional**

Minimum number of identified objects from each input image to use in matching objects from other images. If the default `None` (<https://docs.python.org/3/library/constants.html#None>) value is used then `align` will automatically determine the minimum number of sources from the value of the `fitgeom` parameter. This parameter is used to interrupt alignment process (catalog fitting, WCS “tweaking”) when the number of matched sources is smaller than the value of `minobj` in which case this method will return `False` (<https://docs.python.org/3/library/constants.html#False>).

**fitgeom: {'shift', 'rscale', 'general'}, optional**

The fitting geometry to be used in fitting the matched object lists. This parameter is used in fitting the offsets, rotations and/or scale changes from the matched object lists. The ‘general’ fit geometry allows for independent scale and rotation for each axis. This parameter is ignored if `match` is `False` (<https://docs.python.org/3/library/constants.html#False>).

**nclip: int, None, optional**

Number (a non-negative integer) of clipping iterations in fit. Clipping will be turned off if `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

This parameter is ignored if `match` is `False` (<https://docs.python.org/3/library/constants.html#False>).

**sigma: float, tuple of the form (float, str), optional**

When a tuple is provided, first value (a positive number) indicates the number of “fit error estimates” to use for clipping. The second value (a string) indicates the statistic to be used for “fit error estimate”. Currently the following values are supported: ‘rmse’, ‘mae’, and ‘std’ - see [iter\\_linear\\_fit](#) for more details.

When `sigma` is a single number, it must be a positive number and the default error estimate ‘rmse’ is assumed.

This parameter is ignored when `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0 or when `match` is `False` (<https://docs.python.org/3/library/constants.html#False>).

**clip\_accum: bool, optional**

Indicates whether or not to reset the list of “bad” (clipped out) sources after each clipping iteration. When set to `True` (<https://docs.python.org/3/library/constants.html#True>) the list only grows with each iteration as “bad” positions never re-enter the pool of available position for the fit. By default the list of “bad” source positions is purged

at each iteration. This parameter is ignored when `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

### Returns

#### **bool**

Returns `True` (<https://docs.python.org/3/library/constants.html#True>) if the number of matched sources is larger or equal to `minobj` and all steps have been performed, including catalog fitting and WCS “tweaking”. If the number of matched sources is smaller than `minobj`, this function will return `False` (<https://docs.python.org/3/library/constants.html#False>).

**`apply_affine_to_wcs(ref_tpwcs, matrix, shift, meta=None)`**

Applies a general affine transformation to the WCS.

**`bb_approx_threshold = 50`**

**property `bb_policy`**

Get/set `WCSCatalog` policy for switching to approximate computation of group’s bounding box.

**`calc_tanp_xy(tanplane_wcs)`**

Compute x- and y-positions of the sources from the image catalog in the tangent plane. This creates the following columns in the catalog’s table: ‘TPx’ and ‘TPy’.

### Parameters

**`tanplane_wcs: WCSCorrector`**

A `WCSCorrector` object that will provide transformations to the tangent plane to which sources of this catalog should be “projected”.

**property `catalog`**

Get/set image’s catalog.

**`create_group_catalog()`**

Combine member’s image catalogs into a single group’s catalog.

### Returns

**`group_catalog: astropy.table.Table`**

Combined group catalog.

**`fit2ref(refcat, tanplane_wcs, fitgeom='general', nclip=3, sigma=(3.0, 'rmse'), clip_accum=False)`**

Perform linear fit of this group’s combined catalog to the reference catalog. When either/both group’s catalog or/and the reference catalog contain ‘weight’ column, weighted fitting will be performed. See Notes section for further details.

### Parameters

**`refcat: RefCatalog`**

A `RefCatalog` object that contains a catalog of reference sources.

**tanplane\_wcs: WCSCorrector**

A `WCSCorrector` object that will provide transformations to the tangent plane to which sources of this catalog should be “projected”.

**fitgeom: {'shift', 'rscale', 'general'}, optional**

The fitting geometry to be used in fitting the matched object lists. This parameter is used in fitting the offsets, rotations and/or scale changes from the matched object lists. The ‘general’ fit geometry allows for independent scale and rotation for each axis.

**nclip: int, None, optional**

Number (a non-negative integer) of clipping iterations in fit. Clipping will be turned off if `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**sigma: float, tuple of the form (float, str), optional**

When a tuple is provided, first value (a positive number) indicates the number of “fit error estimates” to use for clipping. The second value (a string) indicates the statistic to be used for “fit error estimate”. Currently the following values are supported: ‘rmse’, ‘mae’, and ‘std’ - see [iter\\_linear\\_fit](#) for more details.

When `sigma` is a single number, it must be a positive number and the default error estimate ‘rmse’ is assumed.

This parameter is ignored when `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**clip\_accum: bool, optional**

Indicates whether or not to reset the list of “bad” (clipped out) sources after each clipping iteration. When set to `True` (<https://docs.python.org/3/library/constants.html#True>) the list only grows with each iteration as “bad” positions never re-enter the pool of available position for the fit. By default the list of “bad” source positions is purged at each iteration. This parameter is ignored when `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

## Notes

When fitting image sources to reference catalog sources, we can specify which sources have higher weights. This can be done by assigning a “weight” to each source by specifying these values in the optional ‘weight’ column of either the reference catalog, image catalog, or both.

When weights are not provided, all sources are weighed equally. When only one of image or reference catalog weights are provided, the sources will be weighted with the specified weights. When *both* image *and* reference catalogs specify weights for the same sources, the two weights will be combined into a single weight as:

$$1/w = 1/w_i + 1/w_r$$

**Warning:** Keep in mind that when a group catalog is created from individual catalogs, weights of the group catalog are created by *concatenating* weights of individual catalogs. Therefore, for the weighting of groups of catalogs to work correctly, the weights of individual catalogs should be scaled in such a way that when individual catalogs are combined into a single “group catalog”, weights preserve their relative values.

For example, let’s say a group is formed from two individual catalogs. Let’s say first catalog contains four sources with equal weights  $[1, 1, 1, 1]$  and the second catalog contains two sources with weights  $[1, 1]$  then the group’s catalogs sources will also have equal weights  $[1, 1, 1, 1, 1, 1]$ . However, if each individual catalog’s weights were normalized such that sum of all weights is 1, then group’s sources will be weighed unequally:  $[0.25, 0.25, 0.25, 0.25, 0.5, 0.5]$ .

#### `get_matched_cat()`

Retrieve only those sources from the catalog that **have been** matched to the sources in the reference catalog.

#### `get_unmatched_cat()`

Retrieve only those sources from the catalog that have **not** been matched to the sources in the reference catalog.

#### `intersection(wcsim)`

Compute intersection of this *WCSGroupCatalog* object and another *WCSImageCatalog*, *WCSGroupCatalog*, or *SphericalPolygon* object.

##### Parameters

**wcsim:** *WCSImageCatalog*, *WCSGroupCatalog*, *SphericalPolygon*

Another object that should be intersected with this *WCSGroupCatalog*.

##### Returns

**polygon:** *SphericalPolygon*

A *SphericalPolygon* that is the intersection of this *WCSGroupCatalog* and *wcsim*.

#### `intersection_area(wcsim)`

Calculate the area of the intersection polygon.

#### `match2ref(refcat, match=None)`

Uses **xyxymatch** to cross-match sources between this catalog and a reference catalog.

##### Parameters

**refcat:** *RefCatalog*

A *RefCatalog* object that contains a catalog of reference sources as well as a valid reference WCS.

**match: MatchCatalogs, function, None, optional**

A callable that takes two arguments: a reference catalog and an image catalog. Both catalogs will have columns 'TPx' and 'TPy' that represent the source coordinates in some common (to both catalogs) coordinate system.

**Returns****nmatches: int**

Number of found matches.

**mref\_idx: numpy.ndarray**

Integer array indicating indices of sources in the reference catalog that were matched to sources in group's catalog.

**minput\_idx: numpy.ndarray**

Integer array indicating indices of sources in group's catalog that were matched to sources in the reference catalog.

**property name**

Get/set *WCSImageCatalog* object's name.

**property poly\_area**

Area of the bounding polygon (in srad).

**property polygon**

Get image's (or catalog's) bounding spherical polygon.

**recalc\_catalog\_radec()**

Recalculate RA and DEC of the sources in the catalog.

**update\_bounding\_polygon()**

Recompute bounding polygons of the member images.

```
class tweakwcs.wcsimage.WCSImageCatalog(catalog, corrector, name=None, group_id=None, meta={})
```

A class that holds information pertinent to an image WCS and a source catalog of the sources found in that image.

**Warning:** If `tpwcs.meta` dictionary contains any of the following keywords 'catalog', 'name', or 'group\_id', they will be ignored without warning.

**Parameters****catalog: astropy.table.Table**

Source catalog associated with an image. Must contain 'x' and 'y' columns which indicate source coordinates (in pixels) in the associated image.

**corrector: WCSCorrector**

WCSCorrector-derived tangent-plane WCS corrector object associated with the image from which the catalog was derived.

**name: str, None, optional**

Image catalog's name. This is used to identify catalog during logging. If name is `None` (<https://docs.python.org/3/library/constants.html#None>), the name of this `WCImageCatalog` object will be set to 'Unknown'.

**group\_id: hashable, None, optional**

Group ID that may be used for identifying catalogs that need to be aligned together. `group_id` must be hashable.

**meta: dict, optional**

Additional information about image, catalog, and/or WCS to be stored (for convenience) within `WCImageCatalog` object.

**property bb\_radec**

Get a tuple of `numpy.ndarray` (<https://numpy.org/doc/stable/reference/generated/numpy.ndarray.html#numpy.ndarray>) of RA and DEC of the vertices of the bounding polygon.

**calc\_bounding\_polygon()**

Calculate bounding polygon of the image or of the sources in the catalog (if catalog was set).

**property catalog**

Get/set image's catalog.

**property corrector**

Get `WCSCorrector` WCS.

**det\_to\_tanp(x, y)**

Convert detector (pixel) coordinates to tangent plane coordinates.

**det\_to\_world(x, y)**

Convert pixel coordinates to sky coordinates using full (i.e., including distortions) transformations.

**property fit\_info**

Get fit information - a dictionary. This class sets only the 'status' field but fitting routines may set additional fields.

**property fit\_status**

Get/Set fit status. This property is a shortcut to the 'status' key value in the `fit_info` dictionary. When the `WCImageCatalog` object is created, `fit_status` is initially set to 'SKIPPED'. Alignment tools are responsible for updating catalog's fit status.

**property group\_id**

Get/set `WCImageCatalog` object's group ID that may be used for identifying catalogs that need to be aligned together. `group_id` must be hashable.

**intersection(wcsim)**

Compute intersection of this `WCImageCatalog` object and another `WCImageCatalog`, `WCSGroupCatalog`, or `SphericalPolygon` object.

**Parameters**

**wcsim:** `WCSImageCatalog`, `WCSGroupCatalog`, `SphericalPolygon`

Another object that should be intersected with this `WCSImageCatalog`.

#### Returns

**polygon:** `SphericalPolygon`

A `SphericalPolygon` that is the intersection of this `WCSImageCatalog` and `wcsim`.

**intersection\_area**(`wcsim`)

Calculate the area of the intersection polygon.

#### property name

Get/set catalog's name. This is used to identify catalog during logging. Upon setting, the value will be converted to a `str` (<https://docs.python.org/3/library/stdtypes.html#str>). When setting to `None` (<https://docs.python.org/3/library/constants.html#None>), the name will be set to 'Unknown'.

#### property poly\_area

Area of the bounding polygon (in srاد).

#### property polygon

Get image's (or catalog's) bounding spherical polygon.

**tanp\_to\_det**(`x`, `y`)

Convert tangent plane coordinates to detector (pixel) coordinates.

**tanp\_to\_world**(`x`, `y`)

Convert tangent plane coordinates to world coordinates.

#### property tpwcs

Deprecated since version 0.8.0: The `tpwcs` property is deprecated and may be removed in a future version.

Get `WCSCorrector` WCS.

**world\_to\_det**(`ra`, `dec`)

Convert sky coordinates to image's pixel coordinates using full (i.e., including distortions) transformations.

**world\_to\_tanp**(`ra`, `dec`)

Convert tangent plane coordinates to detector (pixel) coordinates.

`tweakwcs.wcsimage.convex_hull`(`x`, `y`, `wcs=None`, `min_separation=None`)

Computes the convex hull of a set of 2D points.

Implements [Andrew's monotone chain algorithm](http://en.wikibooks.org/wiki/Algorithm_Implementation/Geometry/Monotone_chain) ([http://en.wikibooks.org/wiki/Algorithm\\_Implementation/Geometry/Monotone\\_chain](http://en.wikibooks.org/wiki/Algorithm_Implementation/Geometry/Monotone_chain)). The algorithm has  $O(n \log n)$  complexity.

Credit: [http://en.wikibooks.org/wiki/Algorithm\\_Implementation/Geometry/Convex\\_hull/Monotone\\_chain](http://en.wikibooks.org/wiki/Algorithm_Implementation/Geometry/Convex_hull/Monotone_chain)

#### Parameters

**x: list, tuple, numpy.ndarray**

An iterable sequence of x-coordinates of points.

**y: list, tuple, numpy.ndarray**

An iterable sequence of y-coordinates of points.

**wcs**

[function] A function that takes two arguments (x, y) and converts them to “world” coordinates. If provided, returned convex hull vertex coordinates will be in “world” coordinates.

**min\_separation**

[None, float] A non-negative number or `None` (<https://docs.python.org/3/library/constants.html#None>). When provided as a number, it specifies the minimum separation in both x and y coordinates between adjacent vertices in the hull. Vertices too close to their neighbors will be removed. This operation is performed `_before_` conversion to “world” coordinates. When `min_separation` is `None` (<https://docs.python.org/3/library/constants.html#None>), all vertices are kept.

## Returns

**Output: list**

A list of vertices of the convex hull in counter-clockwise order, starting from the vertex with the lexicographically smallest coordinates. When a coordinate conversion function is supplied via the `wcs` argument, the returned values are those of the converted vertex coordinates.

## 1.5 linearfit

A module that provides algorithms for performing linear fit between sets of 2D points.

### Authors

Mihai Cara, Warren Hack

### License

*LICENSE*

`tweakwcs.linearfit.build_fit_matrix(rot, scale=1)`

Create an affine transformation matrix (2x2) from the provided rotation angle(s) and scale(s):

$$M = \begin{bmatrix} s_x \cos(\theta_x) & s_y \sin(\theta_y) \\ -s_x \sin(\theta_x) & s_y \cos(\theta_y) \end{bmatrix}$$

### Parameters

**rot: tuple, float, optional**

Rotation angle in degrees. Two values (one for each axis) can be provided as a tuple.



**scale:** tuple, float, optional

Scale of the linear transformation. Two values (one for each axis) can be provided as a tuple.

## Returns

**matrix:** `numpy.ndarray`

A 2x2 `numpy.ndarray` (<https://numpy.org/doc/stable/reference/generated/numpy.ndarray.html#numpy.ndarray>) containing coefficients of a linear transformation.

```
tweakwcs.linearfit.iter_linear_fit(xy, uv, wxy=None, wuv=None, fitgeom='general',
                                   center=None, nclip=3, sigma=(3.0, 'rmse'),
                                   clip_accum=False)
```

Compute linear transformation parameters that “best” (in the sense of minimizing residuals) transform `uv` source position to `xy` sources iteratively using sigma-clipping.

More precisely, this functions attempts to find a 2x2 matrix  $\mathbf{F}$  and a shift vector  $\mathbf{s}$  that minimize the residuals between the *transformed* reference source coordinates `uv`

$$\mathbf{xy}'_k = \mathbf{F} \cdot (\mathbf{uv}_k - \mathbf{c}) + \mathbf{s} + \mathbf{c} \quad (1.1)$$

and the “observed” source positions `xy`:

$$\epsilon^2 = \sum_k w_k \|\mathbf{xy}_k - \mathbf{xy}'_k\|^2. \quad (1.2)$$

In the above equations,  $\mathbf{F}$  is a 2x2 matrix while  $\mathbf{xy}_k$  and  $\mathbf{uv}_k$  are the position coordinates of the  $k$ -th source (row in input `xy` and `uv` arrays).

One of the two catalogs (`xy` or `uv`) contains what we refer to as “image” source positions and the other one as “reference” source positions. The meaning assigned to `xy` and `uv` parameters are up to the caller of this function.

## Parameters

**xy:** `numpy.ndarray`

A (N, 2)-shaped array of source positions (one 2-coordinate position per line).

**uv:** `numpy.ndarray`

A (N, 2)-shaped array of source positions (one 2-coordinate position per line). This array *must have* the same length (shape) as the `xy` array.

**wxy:** `numpy.ndarray`, None, optional

A 1-dimensional array of weights of the same length (N) as `xy` array indicating how much a given coordinate should be weighted in the fit. If not provided or set to `None` (<https://docs.python.org/3/library/constants.html#None>), all positions will be contribute equally to the fit if `wuv` is also set to `None` (<https://docs.python.org/3/library/constants.html#None>). See `Notes` section for more details.

**wuv:** `numpy.ndarray`, None, optional

A 1-dimensional array of weights of the same length (N) as `xy` array indicating how much a given coordinate should be weighted in the fit. If not provided or set to `None` (<https://docs.python.org/3/library/constants.html#None>),

all positions will be contribute equally to the fit if `wxy` is also set to `None` (<https://docs.python.org/3/library/constants.html#None>). See `Notes` section for more details.

**fitgeom: {'shift', 'rshift', 'rscale', 'general'}, optional**

The fitting geometry to be used in fitting the matched object lists. This parameter is used in fitting the shifts (offsets), rotations and/or scale changes from the matched object lists. The 'general' fit geometry allows for independent scale and rotation for each axis.

**center: tuple, list, numpy.ndarray, None, optional**

A list-like container with two `X`- and `Y`-positions of the center (origin) of rotations in the `uv` and `xy` coordinate frames. If not provided, `center` is estimated as a (weighted) mean position in the `uv` frame.

**nclip: int, None, optional**

Number (a non-negative integer) of clipping iterations in fit. Clipping will be turned off if `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**sigma: float, tuple of the form (float, str), optional**

When a tuple is provided, first value (a positive number) indicates the number of “fit error estimates” to use for clipping. The second value (a string) indicates the statistic to be used for “fit error estimate”. Currently the following values are supported: 'rmse', 'mae', and 'std' - see `Notes` section for more details.

When `sigma` is a single number, it must be a positive number and the default error estimate 'rmse' is assumed.

This parameter is ignored when `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

**clip\_accum: bool, optional**

Indicates whether or not to reset the list of “bad” (clipped out) sources after each clipping iteration. When set to `True` (<https://docs.python.org/3/library/constants.html#True>) the list only grows with each iteration as “bad” positions never re-enter the pool of available position for the fit. By default the list of “bad” source positions is purged at each iteration. This parameter is ignored when `nclip` is either `None` (<https://docs.python.org/3/library/constants.html#None>) or 0.

## Returns

**fit: dict**

- 'shift': A `numpy.ndarray` with two components of the computed shift.
- 'shift\_ld': A `numpy.ndarray` with two components of the computed shift of type `numpy.longdouble`.
- 'matrix': A 2x2 `numpy.ndarray` with the computed generalized rotation matrix.

- 'matrix\_ld': A 2x2 `numpy.ndarray` with the computed generalized rotation matrix of type `numpy.longdouble`.
- 'proper\_rot': Rotation angle (degree) as if the rotation is proper.
- 'rot': A tuple of (`rotx`, `roty`) - the rotation angles with regard to the X and Y axes.
- '<rot>': *Arithmetic mean* of the angles of rotation around X and Y axes.
- 'scale': A tuple of (`sx`, `sy`) - scale change in the direction of the X and Y axes.
- '<scale>': *Geometric mean* of scales `sx` and `sy`.
- 'skew': Computed skew.
- 'proper': a boolean indicating whether the rotation is proper.
- 'fitgeom': Fit geometry (allowed transformations) used for fitting data (to minimize residuals). This is copy of the input argument `fitgeom`.
- 'center': Center of rotation
- 'center\_ld': Center of rotation as a `numpy.longdouble`.
- 'fitmask': A boolean array indicating which source positions where used for fitting (`True` (<https://docs.python.org/3/library/constants.html#True>)) and which were clipped out (`False` (<https://docs.python.org/3/library/constants.html#False>)). **NOTE** For weighted fits, positions with zero weights are automatically excluded from the fits.
- 'eff\_nclip': Effective number of clipping iterations
- 'rmse': Root-Mean-Square Error
- 'mae': Mean Absolute Error
- 'std': Standard Deviation of the residuals
- 'resids': An array of residuals of the fit. **NOTE:** Only the residuals for the “valid” points are reported here. Therefore the length of this array may be smaller than the length of input arrays of positions.

## Notes

### Weights

Weights can be provided for both “image” source positions and “reference” source positions. When no weights are given, all positions are weighted equally. When only one set of positions have weights (i.e., either `wxy` or `wuv` is not `None` (<https://docs.python.org/3/library/constants.html#None>)) then weights in (1.2) are set to be equal to the provided set of weights. When weights for *both* “image” source positions and “reference” source positions are provided, then the combined weight that is used in (1.2)

is computed as:

$$1/w = 1/w_{xy} + 1/w_{uv}.$$

### Statistics for clipping

Several statistics are available for clipping iterations and all of them are reported in the returned `fit` dictionary regardless of the setting in `sigma`:

$$\text{RMSE} = \sqrt{\sum_k w_k \|\mathbf{r}_k\|^2}$$

$$\text{MAE} = \sqrt{\sum_k w_k \|\mathbf{r}_k\|}$$

$$\text{STD} = \sqrt{\sum_k w_k \|\mathbf{r}_k - \bar{\mathbf{r}}\|^2 / (1 - V_2)}$$

where  $\mathbf{r}_k = \mathbf{x}\mathbf{y}_k - \mathbf{x}\mathbf{y}'_k$ ,  $\sum_k w_k = 1$ , and  $V_2 = \sum_k w_k^2$ .

## 1.6 wcsutils

A module that provides utility functions for WCS transformations.

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Mihai Cara (contact: [help@stsci.edu](mailto:help@stsci.edu))

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`tweakwcs.wcsutils.planar_rot_3d(angle, axis)`

Create a 3D rotation matrix that performs a rotation *in a plane* perpendicular to the specified *axis*.

## 1.7 linalg

This module provides general purpose and/or specialized linear algebra routines.

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`tweakwcs.linalg.inv(m)`

This function computes inverse matrix using Gauss-Jordan elimination with full pivoting. Computations are performed using `numpy.longdouble` precision. On systems on which `numpy.longdouble` is equivalent to `numpy.double` this function reverts to `numpy.linalg.inv` (<https://numpy.org/doc/stable/reference/generated/numpy.linalg.inv.html#numpy.linalg.inv>) for performance reasons.

### Parameters

**m:** `numpy.ndarray`

A 2D *square* matrix of type `numpy.ndarray`  
(<https://numpy.org/doc/stable/reference/generated/numpy.ndarray.html#numpy.ndarray>).

#### Returns

**invm:** `numpy.ndarray`

Inverse matrix of the input matrix m: a 2D *square* `numpy.ndarray`  
(<https://numpy.org/doc/stable/reference/generated/numpy.ndarray.html#numpy.ndarray>)  
of type `numpy.longdouble` on systems on which it is more accurate than `numpy.double`.

## 1.8 LICENSE

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## DEVELOPMENT NOTES

### 2.1 Release Notes

#### 2.1.1 0.8.7 (29-March-2024)

- Fix a bug in the `imalign.align_wcs` function due to which reference catalog would not get expanded even for successful alignments, essentially disabling `expand_refcat` option. [#201]

#### 2.1.2 0.8.6 (08-January-2024)

- Improved the quality of the *expanded* reference catalog when `expand_refcat` is set to `True` (<https://docs.python.org/3/library/constants.html#True>) in the `align_wcs` function by not using input catalogs that failed to align in the expanded reference catalog. [#195]
- Reduce memory & compute needed by `_xy_2dhist` by pruning distant pairs with a `kdtree`. This is a purely internal change that does not affect the results of the algorithm. [#196]

#### 2.1.3 0.8.5 (30-November-2023)

- Addressed compatibility issues with Python 3.12. Re-organized package setup machinery. [#188]

#### 2.1.4 0.8.4 (unreleased)

- Mistaken tagging.

#### 2.1.5 0.8.3 (12-September-2023)

- Fixed a bug in the `linalg` module due to which computation of the inverse matrix would fallback to custom implementation instead of using `numpy` implementation. [#185]
- Fixed incompatibilities with the future (version 2.0) release of `numpy`. [#185]

### 2.1.6 0.8.2 (13-April-2023)

- Added `bb_policy` argument to the `WCSGroupCatalog` to control when to switch to an approximate method of computing of the bounding polygon of a group of images. The default value is set to 50. Also added equivalent `group_bb_policy` argument to both `fit_wcs` and `align_wcs` functions. [#176]

### 2.1.7 0.8.1 (23-December-2022)

- Fixed a bug in the `XYXYMatch` due to which bin size for the 2D histogram pre-match alignment did not account for the pixel scale in the tangent plane. This required a change in the API of `XYXYMatch`. `__call__` which now `_must_` have `tp_pscale` as input and also inputs catalogs now `_must_` contain 'TPx' and 'TPy' columns. [#173]
- Deprecated 'tp\_wcs' argument of the `XYXYMatch.__call__()` method. Use 'tp\_pscale' instead. [#173]

### 2.1.8 0.8.0 (25-August-2022)

- Exposed in top-level functions parameter `clip_accum` that controls whether or not to reset the list of “bad” (clipped out) sources after each clipping iteration during model fitting. [#169]
- Deprecated `tweakwcs.tpwcs` module in favor of `tweakwcs.correctors`. [#170]
- **Deprecated the following classes in the `tweakwcs.tpwcs` module:**
  - `tweakwcs.tpwcs.TPWCS` in favor of `tweakwcs.correctors.WSCCorrector`;
  - `tweakwcs.tpwcs.JWSTgWCS` in favor of `tweakwcs.correctors.JWSTWCSCorrector`;
  - `tweakwcs.tpwcs.FITSWCS` in favor of `tweakwcs.correctors.FITSWCSCorrector`. [#170]
- Deprecated `tweakwcs.matchutils.TPMatch` class. Use `tweakwcs.matchutils.XYXYMatch` instead. [#170]
- Removed `tanplane_wcs` argument of the `WCSGroupCatalog.apply_affine_to_wcs()` method. `tanplane_wcs` was deprecated since 0.6.5. It was replaced with `ref_tpwcs`. [#170]
- Deprecated `tpwcs` argument of the `WCSImageCatalog.__init__()` as well `tpwcs` property of the same class. Use `corrector` instead. [#170]
- Deprecated `tpwcs` argument of the `tweakwcs.imalign.fit_wcs()` in favor of `corrector`. [#170]



### 2.1.9 0.7.4 (13-April-2022)

This is almost exclusively a maintenance release except for close vertices in the convex hull issue to make the code more robust.

- Set `gwcs` min version to 0.14. [#158]
- Set `astropy` min version to 5.0.4. [#153]
- Remove consecutive convex hull vertices that are very close to each other. [#147]

### 2.1.10 0.7.3 (12-August-2021)

- Fix a bug due to which `minobj` parameter to `WCSGroupCatalog.align_to_ref()` and `align_wcs()` was ignored. [#144]
- Make peak finding code switch to center-of-mass algorithm when estimated 2D parabolic fit estimates a peak outside of the fit box. Reduce accuracy loss in computation. [#143]

### 2.1.11 0.7.2 (13-May-2021)

- Make code more robust to exceptions in the `spherical_geometry` package. [#138]
- Fixed a bug in `matchutils._find_peak()` due to which it could return coordinates of the peak that were outside of the image. [#136]
- Fixed a bug in how re-projection was computed when `center` of the transformations was provided. [#135]

### 2.1.12 0.7.1 (16-February-2021)

- Added support for detecting and using velocity aberration corrected V2-V3 frames when available in JWST WCS ('v2v3vacorr'). [#130]

### 2.1.13 0.7.0 (11-November-2020)

- Added `linearfit.fit_rshift` function to support a new `fitgeom` fitting mode 'rshift' that fits only for shifts and a rotation. [#128]

### 2.1.14 0.6.5 (09-September-2020)

- Added `ref_tpwcs` parameter to `imalign.fit_wcs()`, `imalign.align_wcs()`, `wcsimage.WCSGroupCatalog.align_to_ref()` to allow alignment to be performed in user-specified distortion-free tangent plane. [#125]
- Renamed `tanplane_wcs` parameter in `wcsimage.WCSGroupCatalog.apply_affine_to_wcs()` to `ref_tpwcs`. `tanplane_wcs` parameter was deprecated and will be removed in a future release. [#125]

### 2.1.15 0.6.4 (14-May-2020)

- Bug fix: Unable to initialize JWSTgWCS tangent-plane corrector from an already corrected WCS. [#122]
- Fix a bug in how corrections are applied to a previously corrected JWST WCS. [#120]
- Do not attempt to extract center of linear transformation when not available in '`fit_info`'. [#119]

### 2.1.16 0.6.3 (14-April-2020)

- Fixed a bug due to which reprojection transformation for JWST gWCS was computed at wrong location in the tangent plane. [#118]

### 2.1.17 0.6.2 (07-April-2020)

- When WCS has valid bounding box, estimate scale at the center of the bounding box. [#117]
- Adjust the point at which tangent plane-to-tangent plane transformation is computed by 1/2 pixels for JWST corrections. This correction should have no measurable impact on computed corrections. [#115]

### 2.1.18 0.6.1 (09-March-2020)

- Fixed a bug in applying JWST correction for the case when alignment is performed twice on the same image. Due to this bug the inverse transformation was not updated. [#112]

### 2.1.19 0.6.0 (25-February-2020)

- Fix a possible crash when aligning FITS WCS images due to an unusual way `stwcs.wcsutil.all_world2pix` handles (or not) scalar arguments. [#110]
- Modified the angle at which the reported rotation angles are reported. Now rotation angles have the range `[-180, 180]` degrees. [#109]
- Added support FITS WCS that use PC matrix instead of the CD matrix used in HSTs WCS. [#108]
- Bug fix for alignment of multi-chip FITS images: correction of how transformations from the reference tangent plane are converted to individual images' tangent planes. [#106]

- Significant re-organization of the `fit_info` dictionary. `rot` now becomes `proper_rot` and `rotxy` now becomes `rot` containing only `rotx` and `roty`. Also, `scale` now is a tuple of only two scales `sx` and `sy`. The geometric mean scale is now a separate field '`<scale>`' as well as the arithmetic mean of rotation angles ('`<rot>`'). Finally, '`offset`' in the fit functions from the `linearfit` module was renamed to '`shift`' in order to match the same field returned by functions from the `imalign` module. [#105]
- Linear fit functions now return the fit matrix `F` instead of its transpose. [#100]
- Linear fit functions (in the `linearfit` module) use `longdouble` for internal computations. [#100]
- Re-designed the `JWSTgWCS` corrector class to rely exclusively on basic models available in `astropy` and `gwcs` instead of the `TPCorr` class provided by the `jwst` pipeline. This eliminates the need to install the `jwst` pipeline in order to align JWST images. [#96, #98]

### 2.1.20 0.5.3 (15-November-2019)

- Added logic to allow some input catalogs to be empty and to allow the alignment to proceed as long as there are at least two non-empty (image or group) input catalogs. [#94]

### 2.1.21 0.5.2 (26-July-2019)

- Fixed a deprecation issue in logging and added logic to compute image group's catalog name using a common prefix (if exists) of the names of constituent images. [#92]
- Package version is now handled by `setuptools_scm`. [#93]

### 2.1.22 0.5.1 (08-May-2019)

- Fixed a bug in the “2dhist” algorithm resulting in a crash when 2D histogram has multiple maxima of the same value and no other value larger than one. [#90]

### 2.1.23 0.5.0 (22-April-2019)

- Fixed a bug due to which a warning log message “Failed to align catalog...” would be issued for successful alignments. [#84]
- Fixed a bug in creation of WCS image groups with empty catalogs. [#84]
- Fixed a bug in `match2ref` when it was run in a non-matching mode (`match=None`) due to which it was impossible to detect the case when reference catalog has a different length from a supposedly matched WCS group catalog. [#84]
- Fixed a bug in computation of the bounding polygon of a reference catalog containing only two sources. [#84]
- Fixed a bug in `convex_hull()` resulting in incorrect type being returned in case of empty input coordinate lists or when only one point is provided. [#84]

- Implemented a more robust estimate of the maximum type supported by `numpy.linalg.inv`. [#82]
- Renamed `wcsutils.planar_rot_3D` to `wcsutils.planar_rot_3d`. [#75]
- Renamed `wcsutils.cartesian2spherical` to `wcsutils.cartesian_to_spherical` and `wcsutils.spherical2cartesian` to `wcsutils.spherical_to_cartesian`. [#71]
- Improved “2dhist” algorithm that performs simple catalog pre-alignment used for source matching. [#69]
- Changed the default value of the `searchrad` parameter in `matchutils.TPMatch` to 3. [#69]

#### **2.1.24 0.4.5 (14-March-2019)**

- Fixed incorrect pointer type introduced in previous release [#67].

#### **2.1.25 0.4.4 (13-March-2019)**

- Fixed VS2017 compiler error, “void \*”: unknown size. [#62, #63, #64]

#### **2.1.26 0.4.3 (13-March-2019)**

- Package maintenance release.

#### **2.1.27 0.4.2 (21-February-2019)**

- Fixed a bug due to which the fitting code would crash if `wuv` were provided but `wxy` were set to `None`. [#60]

#### **2.1.28 0.4.1 (14-February-2019)**

- Code cleanup: removed debug print statements. [#59]

#### **2.1.29 0.4.0 (08-February-2019)**

- Matched indices, linear fit results and fit residuals are now set in the input “WCS catalogs” `meta['fit_info']` instead of `meta['tweakwcs_info']`. [#57]
- Updated example notebook to reflect changes to API. [#57]
- Allow `TPWCS` classes to set `meta` during object instantiation. This allows attaching, for example, a source catalog to the tangent-plane WCS corrector object. [#57]
- `align_wcs` no longer supports `NDData` input. Instead catalogs can be provided directly in the `meta` attribute of `TPWCS`-derived WCS “correctors”. This fundamentally transfers the responsibility of instantiating the correct tangent-plane WCS to the caller. This, in turn, will allow future WCS to be supported by providing a custom `TPWCS`-derived corrector defined externally to `tweakwcs` package.

Second benefit is that image data no longer need to be kept in memory in NDData objects as image data are not needed for image alignment once catalogs have been created. [#57]

- Renamed `tweak_wcs` to `fit_wcs` and `tweak_image_wcs` to `align_wcs`. [#57]
- Fixed a bug due to which the code might crash due to an undefined `ra` variable, see issue #55. [#56]
- `tweak_image_wcs()` now returns effective reference catalog used for image alignment. [#54]
- Modified how IDs are assigned to the reference catalog source positions when `expand_refcat` is `True` (<https://docs.python.org/3/library/constants.html#True>): instead of having all sources numbered consecutively starting with 1, now the code will attempt to preserve the original IDs (if any) of the input reference catalog (`refcat`) or an input image used as a reference catalog and consecutively number only the sources being added to the `refcat`. [#54]
- Modified the clipping algorithm to start with all valid sources at each iteration. In other words, clip-pings do not accumulate by default. Old behavior can be replicated by setting `clip_accum` to `True` (<https://docs.python.org/3/library/constants.html#True>). [#53]
- Cleaned-up `iter_linear_fit` interface as well as simplified the `fit` dictionary returned by `iter_linear_fit`. [#53]
- Added option to specify statistics used for clipping. [#51, #52]

### 2.1.30 0.3.3 (21-January-2019)

- Corrected a bug in the non-weighted `rscale` fit. [#49]
- Corrected a bug in the computation of RMSE for the “general” fit. [#47]
- Added computation of MAE of the fit (in addition to RMSE), see [Mean Absolute Error]([https://en.wikipedia.org/wiki/Mean\\_absolute\\_error](https://en.wikipedia.org/wiki/Mean_absolute_error)). [#47]
- Renamed RMSD to RMSE (Root-Mean-Square Error). [#47]

### 2.1.31 0.3.2 (15-January-2019)

- Fixed the formula for computing RMSD of non-weighted fit. [#46]

### 2.1.32 0.3.1 (14-January-2019)

- Fixed Read-The-Docs build failure. [#45]

### 2.1.33 0.3.0 (14-January-2019)

- Implemented higher-accuracy matrix inversion. [#42]
- Bug fix related to not switching to using `bounding_box` instead of `pixel_shape`. [#41]
- Added support for optional 'weight' column in catalogs indicating the weight of each source in fitting linear transformations. [#41]
- Add support for weights to the linear fitting routines. [#40]
- Replaced the use of RMS for each axis with a single RMSD value, see [Root-Mean-Square Deviation]([https://en.wikipedia.org/wiki/Root-mean-square\\_deviation](https://en.wikipedia.org/wiki/Root-mean-square_deviation)). [#40]
- Rely on `pixel_bounds` [see APE 14](<https://github.com/astropy/astropy-APEs/blob/master/APE14.rst>) when available for computation of image's bounding box. [#39]
- Fix a bug in the computation of the world coordinates of the fitted (*aligned*) sources. [#36]

### 2.1.34 0.2.0 (20-December-2018)

- Fix swapped reported reference and input indices of sources used for fitting. [#34]
- Fix for non-initialized C arrays. [#34]
- Changelog correction. [#33]

### 2.1.35 0.1.1 (11-December-2018)

- Fixed a bug due to which 'fit\_ref\_idx' and 'fit\_input\_idx' fields in the fit dictionary were never updated. [#31]
- jwst (pipeline) package is no longer a hard dependency. [#30]
- Removed unnecessary install dependencies. [#30]
- Documentation improvements. [#30, #32]
- Corrected 'RA', 'DEC' units used to compute bounding polygon for the reference catalog. [#30]
- Updated C code to avoid numpy deprecation warnings. [#30]

### 2.1.36 0.1.0 (08-December-2018)

- Added support for aligning FITS WCS. [#15, #16]
- Added keywords to meta attributes of the TPWCS and NDDData to allow easy access to the match and fit information. [#20, #21, #28]
- Package and setup re-design. Support for readthedocs. [#23]
- Documentation improvements. [#17, #18]

- Numerous other bug fixes, code clean-up, documentation improvements and enhancements. [#2, #3, #4, #5, #6, #7, #8, #9, #10, #11, #12, #13, #14, #19, #22, #24, #25, #26, #27, #28, #29]

### **2.1.37 0.0.1 (25-April-2018)**

Initial release. [#1]





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