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# **GaiaLab Documentation**

***Release 0.0.1***

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# CHAPTER 1

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## README file

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Just to check that everything is working.

Note that to add modules (e.g. with automodule) the path to the module should be in conf.py as done previously.



### 2.1 Linux

- Install dependencies (with pip or conda)
- git clone the repository
- Enjoy!

### 2.2 Windows

Not tested but should be similar than Linux

### 2.3 Mac

Not tested but should be similar than Linux





Helpers functions necessary to the core code and plotting functions.

### 3.1 frame\_transformations.py

File `frame_transformations.py` Contains functions that for frame transformations and rotations

**Authors** mdelvallevaro, LucaZampieri (2018)

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**Note:** In this file, when there is a reference, unless explicitly stated otherwise, it refers to Lindegren main article: “The astrometric core solution for the Gaia mission - overview of models, algorithms, and software implementation” by L. Lindegren, U. Lammner, D. Hobbs, W. O’Mullane, U. Bastian, and J.Hernandez The reference is usually made in the following way: Ref. Paper *[LUDW2011]* eq. [1]

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`frame_transformations.adp_to_cartesian(alpha, delta, parallax)`

Convert coordinates from (alpha, delta, parallax) format into the (x, y, z) format.

**Parameters**

- **azimuth** – [rad]
- **altitude** – [rad]
- **parallax** – [mas]

**Returns** [parsec](x, y, z) array in parsecs.

`frame_transformations.compute_ljk(epsilon)`

Ref. *[Lind2001]* (Lindegren, SAG-LL-35, Eq.1)

Calculates ecliptic triad vectors with respect to BCRS-frame.

**Parameters** **epsilon** – obliquity of the equator.

**Returns****np.array, np.array, np.array of the ecliptic triad:**

- **l**: is a unit vector toward  $(\alpha, \delta) = (0,0)^\circ$
- **n**: is a unit vector towards  $\delta = 90^\circ$
- **m** =  $\mathbf{n} \times \mathbf{l}$

`frame_transformations.compute_pqr(alpha, delta)`

Ref. Paper [LUDW2011] eq. [5]

**Can be used also with numpy arrays**

Computes the p, q, r parameters

**Parameters**

- **alpha** – [rad] astronomic parameter alpha
- **delta** – [rad] astronomic parameter alpha

**Returns** p, q, r`frame_transformations.lmn_to_xyz(attitude, vector)`

Ref. Paper [LUDW2011] eq. [9] Goes from the non-rotating (lmn) CoMRS frame to the rotating (xyz) SRS frame

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**Note:** The attitude Quaternion  $q(t)$  gives the rotation from (lmn) to (xyz) (lmn) being the CoMRS (C), and (xyz) the SRS (S). The relation between the two frames is given by:  $\{S'v, 0\} = q^{-1} \{C'v, 0\} q$  for an any vector  $v$ 

---

**Parameters**

- **attitude** – Quaternion object
- **vector** – array of 3D

**Returns** the coordinates in XYZ-frame of the input vector.`frame_transformations.polar_to_direction(alpha, delta)`

Convert polar angles to unit direction vector

**Parameters**

- **alpha** – [rad]
- **delta** – [rad]

**Returns** 3D np.array unit vector`frame_transformations.quat_to_vector(quat)`**Parameters** **quat** – [quaternion] Quaternion to transform into vector**Returns** 3D array made with x,y,z components of the quaternion`frame_transformations.rotate_by_quaternion(quaternion, vector)`

Ref. Paper [LUDW2011] eq. [9] rotate vector by quaternion

`frame_transformations.transform_twoPi_into_halfPi (deltas)`

Transforms an angle in range  $[0-2\pi]$  to range  $[-\pi/2, \pi/2]$  by subtracting  $2\pi$  to any angle greater than  $\pi$ .

**Warning:** The input angles have to be defined between  $[0, \pi/2]$  and  $[3\pi/2, 2\pi]$

**Parameters** `delta` – input angles

**Returns** modified angles

`frame_transformations.vector_to_alpha_delta (vector, two_pi=False)`

Ref. Paper [LUDW2011] eq. [96] Convert cartesian coordinates of a vector into its corresponding polar coordinates ( $0 - 2\pi$ )

**Parameters**

- **vector** – [array] X,Y,Z coordinates in CoMRS frame (non-rotating)
- **two\_pi** – [bool] if True return delta in  $[0, 2\pi]$  instead of  $[-\pi/2, \pi/2]$

**Returns** [rad][rad] alpha, delta

`frame_transformations.vector_to_quat (vector)`

Transform vector to quaternion by setting x,y,z components of the quaternion with x,y,z components of the vector.

**Parameters** `vector` – vector to transform to quaternion

**Returns** quaternion created from vector

`frame_transformations.xyz_to_lmn (attitude, vector)`

Ref. Paper [LUDW2011] eq. [9] Go from the rotating (xyz) SRS frame to the non-rotating (lmn) CoMRS frame

---

**Note:** The attitude Quaternion  $q(t)$  gives the rotation from (lmn) to (xyz) (lmn) being the CoMRS (C), and (xyz) the SRS (S). The relation between the two frames is given by:  $\{C^v, 0\} = q \{S^v, 0\} q^{-1}$  for an any vector  $v$

---

**Parameters**

- **attitude** – Quaternion object
- **vector** – array of 3D

**Returns** the coordinates in LMN-frame of the input vector.

`frame_transformations.zero_to_two_pi_to_minus_pi_pi (angle, unit='radians')`

Transforms an angle in range  $[0-2\pi]$  to range  $[-\pi, \pi]$  by subtracting  $2\pi$  to any angle greater than  $\pi$ .

Info: Can be used with numpy arrays

**Parameters**

- **angle** – [rad] angle or array of angles in  $[0-2\pi]$  format
- **unit** – [str] specify if the input data is in radians or degrees

**Returns** angle in the  $[-\pi, \pi]$  format

## 3.2 helpers.py

File helpers.py

Helper functions for the analytic scanner

**Contains: (at least)**

- `compute_intersection`
- `compute_angle`

**Author** LucaZampieri (2018)

`helpers.check_symmetry(a, tol=1e-12)`

Check the symmetry of array a. True if symmetric up to tolerance

`helpers.compute_angle(v1, v2)`

Computes the angle between two Vectors :param vi: vector between which you want to compute the angle for each i=1:2 :returns: [float] [deg] angle between the vectors

`helpers.compute_intersection(x1, y1, x2, y2, x3, y3, x4, y4, segment=True)`

Return intersection of two lines (or segments) if it exists, raise an error otherwise. :param xi: x-coordinate of segment i for i=1:4 :param yi: y-coordinate of segment i for i=1:4 :param segment: [bool]

**Returns**

- (x, y) tuple with x and y coordinartes of the intersection point
- [list] error\_msg list

`helpers.get_rotation_matrix(v1, v2)`

Get the rotation matrix necessary to go from v1 to v2 :param vi: 3D vector as np.array To rotate vector v1 into v2 then do `r@v1`

`helpers.get_sparse_diagonal_matrix_from_half_band(half_band)`

it assumes we have the upper hal of the band, i.e. we some zeros at the bottom of band for column index greater than 0

`helpers.normalize(v, tol=1e-10)`

return normalized version of v

`helpers.plot_sparsity_pattern(A, tick_frequency)`

**Parameters** **A** – np array containing the matrix

`helpers.sec(x)`

Stable if x close to 0

`helpers.symmetrize_triangular_matrix(a)`

Symmetrize an already triangular matrix (lower or upper) :param a: upper ot lower triangular matrix :returns: corresponding symmetric matrix

## 3.3 analytic\_plots.py

Here is described the list of files documented and corresponding functions for the core part of the code. Helper functions and plotting functions are documented apart, under auxiliary code.

### 4.1 satellite.py

Satellite class implementation in Python

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#### Todo:

- repair attitude for  $t_{\text{init}} \neq 0$
- 

**Author** mdelvallevaro

`satellite.gaia_orbit` ( $t$ ,  $\epsilon$ )

#### Parameters

- **t** – time at which we want the position
- **epsilon** – obliquity of equator

**Returns** the gaia position at time **t**, assuming it is a circle around the sun tilted by epsilon:

**class** `satellite.Satellite` ( $t_i=0$ ,  $t_f=1825$ ,  $dt=0.041666666666666664$ ,  $k=3$ ,  $*args$ )

Class Object, that represents a satellite, e.g. Gaia.

Creates spline from attitude data for 5 years by default.

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**Note:** (see e.g. Lindegren, SAG-LL-35)

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The Nominal Scanning Law (NSL) for gaia is descibed by two constant angles:

- Epsilon: obliquity of equator
- Xi (greek letter): revolving angles

and 3 angles that increase continuously but non-uniformly:

- $\lambda(t)$ : nominal longitude of the sun
- $\nu(t)$ : revolving phase
- $\omega(t)$ : spin phase

With also initial values  $\nu(0)$ ,  $\omega(0)$  at time  $t_0$  the NSL is completely specified.

`__init__` ( $t_i=0$ ,  $t_f=1825$ ,  $dt=0.041666666666666664$ ,  $k=3$ ,  $*args$ )

#### Parameters

- **$t_i$**  – initial time, float [day]
- **$t_f$**  – final time, float [day]
- **$dt$**  – time step for creation of discrete data fed to spline, float [day].
- **$S$**  – change in the z-axis of satellite wrt solar longitudinal angle. [float]
- **$\epsilon$**  – ecliptical angle [rad]
- **$\xi$**  – revolving angle [rad]
- **$w_z$**  – z component of inertial spin vector [arcsec/s]

**Action** Sets satellite to initialization status.

**`orbital_period`** = **`None`**  
orbital\_period [days]

**`orbital_radius`** = **`None`**  
orbital\_radius

**`spline_degree`** = **`None`**  
degree of the interpolating polynomial. `spline_degree` = `spline_order` - 1

**`init_parameters`** ( $S=4.035$ ,  $\epsilon=0.4090928042223289$ ,  $\xi=0.9599310885968813$ ,  $w_z=60$ )  
Init parameters with values in file `constants.py`

**`ephemeris_bcrs`** ( $t$ )  
Defines the orbit of the satellite around the sun Returns the barycentric ephemeris of the Gaia satellite at time  $t$ . Equivalently written  $b_G(t)$

**Parameters**  **$t$**  – float [days]

**Returns** [np.array] 3D [AU] BCRS position-vector of the satellite

**`reset`** ( $t_i$ ,  $t_f$ ,  $dt$ )

**Returns** reset satellite to initialization status

## 4.2 source.py

Source class implementation in Python

**Authors** mdelvallevaro LucaZampier (modifications)

`source.compute_topocentric_direction(astro_parameters, sat, t)`

Compute the topocentric\_function direction i.e.  $\hat{u}$ . The horizontal coordinate system, also known as topocentric coordinate system, is a celestial coordinate system that uses the observer's local horizon as the fundamental plane. Coordinates of an object in the sky are expressed in terms of altitude (or elevation) angle and azimuth.

#### Parameters

- **astro\_parameters** – [alpha, delta, parallax, mu\_alpha\_dx, mu\_delta, mu\_radial] [rads]  
the astrometric parameters
- **sat** – [Satellite]
- **t** – [float][days] time at which we want the topocentric function

**Returns** [array] (x,y,z) direction-vector of the star from the satellite's lmn frame. (CoMRS)

**class** `source.Source`(*name, alpha0, delta0, parallax, mu\_alpha, mu\_delta, radial\_velocity, func\_color=<function Source.<lambda>>, mean\_color=0*)

Source class implemented to represent a source object in the sky

Examples:

```
>>> vega = Source("vega", 279.2333, 38.78, 128.91, 201.03, 286.23, -13.9)
>>> proxima = Source("proxima", 217.42, -62, 768.7, 3775.40, 769.33, 21.7)
>>> sirio = Source("sirio", 101.28, -16.7161, 379.21, -546.05, -1223.14, -7.6)
```

**\_\_init\_\_** (*name, alpha0, delta0, parallax, mu\_alpha, mu\_delta, radial\_velocity, func\_color=<function Source.<lambda>>, mean\_color=0*)

#### Parameters

- **alpha0** – [deg]
- **delta0** – [deg]
- **parallax** – [mas]
- **mu\_alpha** – [mas/yr]
- **mu\_delta** – [mas/yr]
- **radial\_velocity** – [km/s]
- **func\_color** – function representing the color of the source in nanometers
- **mean\_color** – mean color observed by satellite

**Transforms in rads/day or rads, i.e. we got:**

- [alpha] = rads
- [delta] = rads
- [parallax] = rads
- [mu\_alpha\_dx] = rads/days
- [mu\_delta] = rads/days
- [mu\_radial] = rads/days

**get\_parameters** (*t=0*)

**Returns** astrometric parameters at time t (t=0 by default)

**reset ()**

Reset star position to  $t=0$

**set\_time (t)**

Sets star at position wrt bcrs at time  $t$ .

**Parameters**  $t$  – [float][days] time

**barycentric\_direction (t)**

Direction unit vector to star from bcrs.

**Parameters**  $t$  – [float][days]

**Returns** ndarray 3D vector of [floats]

**barycentric\_coor (t)**

Vector to star wrt bcrs-frame.

alpha: [float][rad] delta: [float][rad] parallax: [float][rad] :param  $t$ : [float][days] :return: ndarray, length 3, components [floats][parsecs]

**unit\_topocentric\_function (satellite, t)**

Compute the topocentric\_function direction

**Parameters** **satellite** – satellite [class object]

**Returns** [array] (x,y,z) direction-vector of the star from the satellite's lmn frame.

**topocentric\_angles (satellite, t)**

Calculates the angles of movement of the star from bcrs.

**Parameters**

- **satellite** – satellite object
- $t$  – [days]

**Returns** alpha, delta, delta alpha, delta delta [mas]

## 4.3 scanner.py

Scanner class implementation in Python

**Authors** LucaZampieri (2018) mdelvallevaro (2018)

`scanner.eta_angle (t, sat, source, FoV='centered')`

Function to minimize in the scanner.

See `agis_functions.observed_field_angles()`

**Parameters** **FoV** – [string] specify which Field of View to use

`scanner.get_etas_fromphis (phi_a, phi_b, FoV)`

Tranform phis into etas using the field of view parameter

**Parameters**

- **phi\_a** – phi at the beginning of the interval
- **phi\_b** – phi at the end of the interval
- **FoV** – [string] specify which Field of View we are using



**Returns** eta at the beginning and end of the interval

`scanner.violated_constraints(eta_a, zeta_a, eta_b, zeta_b, zeta_limit)`

**Returns** True if the constraints are violated and False otherwise

**class** `scanner.Scanner(zeta_limit=0.008726646259971648, double_telescope=True)`

`__init__(zeta_limit=0.008726646259971648, double_telescope=True)`

#### Parameters

- **zeta\_limit** – [rads] limitation of the Field of View in the across scan direction
- **double\_telescope** – [bool] if true implements the scanner version with two telescopes (gaia-like)

**reset** (*verbose=False*)

**Action** empty all attribute lists from scanner before beginning new scanning period.

**Parameters** **verbose** – [bool] If true will print messages

**scan** (*sat, source, ti, tf*)

Find the exact time in which the source is seen.

**Action** Find the observation time of the sources

#### Parameters

- **sat** – [Satellite object]
- **source** – [Source object]
- & **tf** (*ti*) – [days] initial and end dates

**Returns** [float] time it took for the scan

**compute\_angles\_eta\_zeta** (*sat, source*)

Compute angles and remove ‘illegal’ observations ( $|zeta| > zeta_{lim}$ )

**scanner\_error** ()

**Returns** mean error in the Along-scan direction

## 4.4 agis.py

**File** agis.py

**purpose** Contains implementation of classes Calc\_source and Agis

**Authors** LucaZampieri

Description of what we are trying to achieve in this file:

**class** `agis.Calc_source(name=None, obs_times=[], source_params=None, mu_radial=None, mean_color=0, source=None)`

Contains the calculated parameters per source

`__init__(name=None, obs_times=[], source_params=None, mu_radial=None, mean_color=0, source=None)`

Data structure containing our computed parameters for the source in question.

#### Parameters

- **name** – [string] the name of the source
- **obs\_times** – [list or array] of the observed times for this source
- **source\_params** – [list or array] alpha, delta, parallax, mu\_alpha, mu\_delta
- **mu\_radial** – [float] radial velocity of the source (apart since we do not solve for radial velocity)
- **mean\_color** – [float] mean color of the source if we want to use explore chromatic aberration
- **source** – [source] instead of most of the above parameters we can provide a source object instead and take the data from it. Manually providing the parameters will override the source parameter

see `source.Source`

```
>>> calc_source = Calc_source('calc_sirio', [1, 2.45, 12], [1, 2, 3, 4, 5], 6)
>>> calc_source = Calc_source(obs_times=[1, 2, 3], source=sirio) # where_
↳sirio is a source object
```

```
class agis.Agis(sat, calc_sources=[], real_sources=[], attitude_splines=None, verbose=False,
                spline_degree=3, attitude_regularisation_factor=0, updating='attitude', de-
                gree_error=0, double_telescope=False)
```

```
__init__(sat, calc_sources=[], real_sources=[], attitude_splines=None, verbose=False,
         spline_degree=3, attitude_regularisation_factor=0, updating='attitude', degree_error=0,
         double_telescope=False)
```

#### Parameters

- **sat** – [Satellite]
- **calc\_sources** – [list of Calc\_sources]
- **real\_sources** – [liste of Sources]
- **attitude\_splines** – list of splines, only if we update attitude
- **verbose** – [bool] if True prints intermediate results
- **spline\_degree** – degree of the splines
- **attitude\_regularization\_factor** – [float] lambda in the paper. Describes how much we take into account the regularization into our minimization problem
- **updating** – [string] defines what we are currently updating can be: 'source', 'scanned source' or 'attitude'
- **degree\_error** –
- **double\_telescope** – [bool] if True uses two telescopes (gaia-like)

**real\_sources = None**

List of the sources objects

**calc\_sources = None**

List of calculated sources with 1-1 correspondance to the real sources

**sat = None**

Satellite object that we are using to solve the problem

**k = None**

Degree of the interpolating polynomial

**M = None**

Order of the spline (degree+1)

**time\_dict = None**

[dict] containing the observed times associated with their source index

**all\_obs\_times = None**

[array] containing the combined observation time of all the sources

**reset\_iterations ()**

Resetting the iteration counter

**error\_function ()**

Ref. Paper [LUDW2011] eq. [24]

Compute the error function Q

$$Q = \sum_{l \in AL} (R^{AL})^2 + \sum_{l \in AC} (R^{AC})^2$$

**get\_field\_angles (source\_index, t)**

Uses functions `get_attitude_for_source()`, `get_attitude()`, `observed_field_angles()`, `calculated_field_angles()`, `satellite.Satellite.func_attitude()`

#### Parameters

- **source\_index** – [int] index of the source
- **t** – [float] [days] time at which

**Returns** eta\_obs, zeta\_obs, eta\_calc, zeta\_calc

**deviate\_field\_angles\_color\_aberration (source\_index, t, angles)**

apply color aberration deviation to field angles (eta, zeta)

---

**Note:** If we the color aberration is not given in the sources, nothing happens and the same angles are returned.

---

**compute\_R\_L (source\_index, t)**

Ref. Paper [LUDW2011] eq. [25]-[26].

$$R = \eta_{obs} + \zeta_{obs} - \eta_{calc} - \zeta_{calc}$$

**Note** R\_AL = R\_eta, R\_AC = R\_zeta

**Returns** [tuple] R\_eta, R\_zeta

**iterate (num, use\_sparse=False, verbosity=0)**

Do \_num\_ iterations

**update\_S\_block ()**

Performs the update of the source parameters

**update\_block\_S\_i (source\_index)**

Ref. Paper [LUDW2011] eq. [57]

Uses function `block_S_error_rate_matrix()`

**Parameters** `source_index` – [int] Index of the source that will be updated

**Action** update source number `source_index`

`compute_h(source_index)`

Ref. Paper [LUDW2011] eq. [59]

Source update Right hand side

Uses functions `compute_R_L()`

**Warning:** here we sum along-scan and across-scan observations. It should be good for this update, but be carefull in future implementations

**Parameters** `source_index` – [int] Index of the source that will be updated

`block_S_error_rate_matrix(source_index)`

Ref. Paper [LUDW2011] eq. [58]

error matrix for the block update S

uses `compute_du_ds()` and `dR_ds()`

**Parameters** `source_index` – [int] Index of the source that will be updated

`dR_ds(source_index, du_ds)`

Ref. Paper eq. [71] Computes the derivative of the error ( $R_l$ ) wrt the 5 astronomic parameters  $s_i$  transposed.

**Parameters**

- **`source_index`** – [int] Index of the source that will be updated
- **`du_ds`** – [numpy array] derivative of the topocentric function wrt astronomic parameters

**Returns** [tuple of numpy arrays] with derivatives of observations in the Along-scan (AL) and Across-scan (AC) directions

`compute_du_ds(source_index)`

Ref. Paper [LUDW2011] eq. [73]

Compute  $d\mathbf{u}_ds$  for a given source

---

**Note:**

- $b_G(t)$  barycentric position of Gaia at the time of observation, also called barycentric ephemeris of the Gaia Satellite
- $t_B$  barycentric time (takes into account the Römer delay)
- $t_{ep}$  in the paper is not used since we assume  $t_{ep}=0$  and start counting the time from J2000

Uses `CoMRS_to_SRS_for_source_derivatives()`, `satellite.Satellite.ephemeris_bcrs()` and `agis_functions.compute_du_dparallax()`

**Parameters** `source_index` – [int] Index of the source that will be updated

**Returns** `du_ds` - source derivatives (wrt astrometric parameters) in SRS

**CoMRS\_to\_SRS\_for\_source\_derivatives** (`CoMRS_derivatives`, `calc_source`, `t_L`, `source_index`)

Ref. Paper [LUDW2011] eq. [72]

rotate the frame from CoRMS (lmn) to SRS (xyz) for the given derivatives

#### Parameters

- **CoMRS\_derivatives** – [list] of derivatives [du\_dalpha, du\_ddelta, du\_dparallax, du\_dmualpha, du\_dmudelta]
- **calc\_source** – [Calc\_source]
- **t\_L** – [float] time of observation
- **source\_index** – [int]

**get\_attitude\_for\_source** (`source_index`, `t`)

For only source updating with **color aberration**. Change if condition to decide which sources are affected by that aberration

#### Parameters

- **source\_index** – [int] Index of the source that will be updated
- **t** – [float] [days] time at which we want the attitude

**get\_attitude** (`t`, `unit=True`)

Get attitude from the attitude coefficients at time `t`. If `unit` is True, the return normalized attitude.

#### Parameters

- **t** – [float] time at which we desire the attitude
- **unit** – [bool] if true normalize the quaternion

**Returns** [Quaternion object] attitude

**actualise\_splines** ()

**Action** Update the splines re-creating them from the new coefficients

**update\_A\_block** (`use_sparse=False`)

Ref. Paper [LUDW2011] Section 5.2

Solve for the attitude

**update\_A\_block\_bis** ()

updates the four components separately (wrong but not by much)

It should work if we update just some of the blocks (like one or two)

**compute\_attitude\_LHS** ()

Ref. Paper [LUDW2011] eq. [82]

**compute\_attitude\_RHS()**

Ref. Paper [LUDW2011] eq. [82]

**get\_source\_index(t)**

get the index of the source corresponding to observation time t

**Parameters** **t** – [float] observation time

**Returns** [int] source index

**compute\_attitude\_RHS\_n(n\_index)**

Ref. Paper [LUDW2011] eq. [82]

**Parameters** **n\_index** –

**Returns** entry **n** of the Right Hand Side column vector for the attitude update

**compute\_Naa\_mn(m\_index, n\_index)**

Ref. Paper [LUDW2011] eq. [82]

compute dR/da (i.e. wrt coeffs)

**Parameters**

- **m\_index** –

- **n\_index** –

**Returns** entry [n, m] of the attitude normal matrix **N\_a**

**compute\_attitude\_banded\_derivative\_and\_regularisation\_matrices()**

Ref. Paper [LUDW2011] eq. [82]

Computes the bands of the banded matrices of the derivatives for the normal matrix and the band for the regularization of the normal matrix.

**Returns** (der\_band, reg\_band)

**compute\_sparses\_matrices(der\_band, reg\_band)**

**Action** Creates sparse banded matrices from bands and stores them in class properties

**Parameters**

- **der\_band** – band for the derivatives part of the normal attitude matrix

- **reg\_band** – band for the regularization part of the normal attitude matrix

**compute\_matrix\_reg\_mn(m\_index, n\_index)**

Ref. Paper [LUDW2011] eq. [82]

compute  $\lambda^2 * \frac{dD_l}{da_m} * \frac{dD_l}{da_n} da_n^T$  (i.e. wrt coeffs)

**Parameters**

- **m\_index** – [int]

- **n\_index** – [int]

**Returns** reg\_mn [n, m] entry of the regularisation part of the attitude normal matrix

`compute_matrix_der_mn(m_index, n_index)`

Ref. Paper [LUDW2011] eq. [82]

Compute  $\frac{dR_l}{da_n} \frac{dR_l}{da_m}$  (i.e. wrt coeffs)

**Parameters**

- **m\_index** – [int]
- **n\_index** – [int]

**Returns** der\_mn, entry [n ,m] of the derivative parts of the attitude normal matrix

## 4.5 agis\_functions.py

**File** agis\_functions.py

**purpose** Functions that uses the classes source, satellite but don't belong to a given file yet

**used by** (at least) agis.py & scanner.py

**author** LucaZampieri

The file is divided in sections, one for each purpose they serve.

When cleaning this file search for ???, LUCa, warning , error, debug, print?

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**Note:** In this file, when there is a reference, unless explicitly stated otherwise, it refers to Lindegren main article: “The astrometric core solution for the Gaia mission - overview of models, algorithms, and software implementation” by L. Lindegren, U. Lammer, D. Hobbs, W. O’Mullane, U. Bastian, and J.Hernandez The reference is usually made in the following way: Ref. Paper [LUDW2011] eq. [1]

---

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**Todo:**

- [DONE] Rotate the attitude
  - [DONE] attitude i.e. generate observations (with scanner object but without scanning)
  - [DONE] with scanner
  - [DONE] two telescope
  - Attitude with scanner
  - scaling
- 

---

**Todo:** (bis)

- implement chromatic aberration
- add acceleration to proper motion
- add noise to observation
- QSO
- signal

- binary source
- 

`agis_functions.add_noise_to_calc_source(s, noise=1e-12)`

**Action** Adds noise to given calc\_source (inline)

**Parameters**

- **s** – [calc\_source object] that we wish to make noisy
- **noise** – [numpy array] of five elements, one for each parameter of the source

`agis_functions.attitude_from_alpha_delta(source, sat, t, vertical_angle_dev=0)`

**Parameters**

- **source** – [Source object]
- **sat** – [satellite object]
- **t** – [float] time
- **vertical\_angle\_dev** – how much we deviate from zeta

`agis_functions.calculated_field_angles(calc_source, attitude, sat, t, double_telescope=False)`

Ref. Paper [LUDW2011] eq. [12]-[13]

Return field angles according to Lindegren eq. 12. See `compute_field_angles()`

**Parameters**

- **source** – [Calc\_source]
- **attitude** – [quaternion] attitude at time t
- **sat** – [Satellite]
- **t** – [float] time at which we want the angles
- **double\_telescope** – [bool] If true, uses the model with two telescopes

**Returns**

- eta: along-scan field angle (== phi if double\_telescope = False)
- zeta: across-scan field angle

`agis_functions.compare_attitudes(gaia, solver, my_times)`

**Parameters**

- **gaia** – [satellite object]
- **solver** – [Solver object]
- **my\_times** – [list][days] list of times at which we want to compare the attitudes

**Returns** figure object

`agis_functions.compute_DL_da_i(coeff_basis_sum, bases, time_index, i)`

Ref. Paper [LUDW2011] eq. [80]

Compute derivative of the attitude deviation wrt attitude params. See `compute_coeff_basis_sum()`



**Parameters**

- **coeff\_basis\_sum** – the sum  $\sum_{n=L-M+1}^L a_n B_n(t_L)$
- **bases** – Bspline basis,  $B_n(t_L)$  in the equation above.
- **time\_index** – [int] index that will get us to return  $B_n(t_L)$ . Since we stored only  $B_n$  for all the observed times  $t_L$ , it is possible to access them only with the index
- **i** – number of the base that we want (**n in the equations above**)

`agis_functions.compute_DL_da_i_from_attitude(altitude, bases, time_index, i)`

Ref. Paper [LUDW2011] eq. [83]

Compute derivative of the attitude deviation wrt attitude params. See `compute_coeff_basis_sum()`

**Parameters**

- **attitude** – [quaternion]
- **bases** – Bspline basis,  $B_n(t_L)$  in the equation above.
- **time\_index** – [int] index that will get us to return  $B_n(t_L)$ . Since we stored only  $B_n$  for all the observed times  $t_L$ , it is possible to access them only with the index
- **i** – number of the base that we want (**n in the equations above**)

`agis_functions.compute_attitude_deviation(coeff_basis_sum)`

Ref. Paper [LUDW2011] eq. [80]

Compute the attitude deviation from unity:

$$D_l = 1 - \left\| \sum_{n=L-M+1}^L a_n B_n(t_L) \right\|^2$$

**Action** Compute the attitude deviation from unity

**Parameters** **coeff\_basis\_sum** – the sum  $\sum_{n=L-M+1}^L a_n B_n(t_L)$

**Returns** attitude deviation from unity

`agis_functions.compute_coeff_basis_sum(coeffs, bases, L, M, time_index)`

Ref. Paper [LUDW2011] eq. [80]

Computes the sum:

$$\sum_{n=L-M+1}^L (a_n \cdot B_n(t_L))$$

**Parameters**

- **coeffs** – [numpy array] splines coefficients
- **bases** – [numpy array] B-spline bases
- **L** – [int] left\_index
- **M** – [int] spline order (= spline degree + 1)
- **time\_index** – [float] time index where we want to evaluate the spline

**Returns** [numpy array] vector of the  
`agis_functions.compute_dR_dq(calc_source, sat, attitude, t)`

Ref. Paper [LUDW2011] eq. [79].

Computes the derivative of the cost-function w.r.t. quaternion  $q$  i.e. the tuple of equations:

- $\frac{dR_i^{AL}}{dq_l} = 2 \cdot \sec(\zeta_l) q_l * \{S' n_l, 0\}$  which is Along\_scan w.r.t. observation number  $l$
- $\frac{dR_i^{AC}}{dq_l} = -2q_l * \{S' m_l, 0\}$

where  $*$  is a quaternion multiplication

**Parameters**

- **calc\_source** – [calc\_source object]
- **sat** – [sat object]
- **attitude** – [numpy quaternion]
- **t** – [float][days] time

**Returns** [tuple of numpy arrays] ( $dR^{AL}/dq$ ,  $dR^{AC}/dq$ )

`agis_functions.compute_deviated_angles_color_aberration(eta, zeta, color, error)`

Implementation of chromatic aberration

**Parameters**

- **eta** –
- **zeta** –
- **color** –
- **error** –

**Returns**

- eta deviated by the aberration
- zeta deviated by the aberration

`agis_functions.compute_du_dparallax(r, b_G)`

Ref. Paper [LUDW2011] eq. [73]

Computes  $\frac{du}{d\omega}$

**Parameters**

- **r** – barycentric coordinate direction of the source at time  $t$ . Equivalently it is the third column vector of the “normal triad” of the source with respect to the ICRS.
- **b\_G** – Spatial coordinates in the BCRS.

**Returns** [array] the derivative  $du_{dw}$

`agis_functions.compute_field_angles(Su, double_telescope=False)`

Ref. Paper [LUDW2011] eq. [12]-[13]

Return field angles according to eq. [12]

**Parameters**

- **Su** – array with the proper direction in the SRS reference system
- **double\_telescope** – [bool] If true, uses the model with two telescopes

**Returns**

- eta: along-scan field angle (== phi if double\_telescope = False)
- zeta: across-scan field angle

`agis_functions.compute_mnu(phi, zeta)`

Ref. Paper [LUDW2011] eq. [69]

$$S'm_l = [-\sin(\phi_l), \cos(\phi_l), 0]^T$$

$$S'n_l = [-\sin(\zeta_l)\cos(\phi_l), -\sin(\zeta_l)\sin(\phi_l), \cos(\zeta_l)]^T$$

$$S'u_l = [\cos(\zeta_l)\cos(\phi_l), \cos(\zeta_l)\sin(\phi_l), \sin(\zeta_l)]^T$$

**Parameters**

- **phi** – [float]
- **zeta** – [float]

**Returns** [array] column vectors of the  $S'[m_l, n_l, u_l]$  matrix

`agis_functions.dR_da_i(dR_dq, bases_i)`

See `compute_dR_dq()`

**Parameters**

- **dR\_dq** – Derivative of the cost functions w.r.t. the quaternion q
- **basis\_i** – B-spline basis of index i

`agis_functions.error_between_func_attitudes(my_times, func_att1, func_att2)`

Computes the sum of the relative difference of the quaternion components between two attitudes

**Parameters**

- **my\_times** – times at which the difference will be computed
- **func\_att1** – [function] that returns an attitude quaternion to compare
- **func\_att2** – [function] that returns an attitude quaternion to compare

**Returns** [float] The error in attitude (only qualitative) just for visualization

`agis_functions.extend_knots(internal_knots, k)`

Extend the knots sequence to add the external knots. This is done because `extract_coeffs_knots_from_splines()` returns only the internal knots. Therefore they should be extended on both sides by **k** knots.

**Parameters**

- **internal\_knots** – [array] containing the internal knots
- **k** – [int] spline degree

**Returns** [list] containing the extended knots

`agis_functions.extract_coeffs_knots_from_splines (attitude_splines, k)`

Extract spline characteristics (coeffs, knots, splines). The spline being defined as

$$S(t) = \sum_{n=0}^{N-1} a_n B_n(t)$$

where  $c_n$  are the spline coefficients and  $B_n(t)$  is the spline basis evaluated at time  $t$ .  $N$  is the number of coefficients. The knots are the time discretization used for the spline.

**Parameters**

- **attitude\_splines** – list or array of splines of `scipy.interpolate.InterpolatedUnivariateSpline`
- **k** – [int] Spline degree

**Returns**

- [array] coeff
- [array] knots
- [array] splines (Bspline interpolating with degree  $k$ )

`agis_functions.generate_angles_of_sources (times_for_source, sat, noise_factor=1e-12)`

Create source along the path of the telescopes. For each time in `times_for_source` create one source on PFOV, one between the two telescope and one on the FFOV returns a number `num_sources` x3 of ICRS coordinates (right ascension, declination)

**Parameters**

- **num\_source** – [list of floats] times where we want to create the sources
- **noise\_factor** – [float]

**Returns** list of alphas and deltas

`agis_functions.generate_observation_wrt_attitude (attitude)`

Create coordinates of a star in the position of the x-axis of the attitude of the satellite

**Parameters** **attitude** – The attitude of the satellite

**Returns** [tuple of floats] [rads]right ascention and declination corresponding to the direction in which the x-vector rotated to *attitude* is pointing

`agis_functions.generate_scanned_times_intervals (day_list, time_step)`

Given a list of days, it will return the list of time that will define the intervals to be scanned

**Parameters**

- **day\_list** – [list of floats][days]
- **time\_step** – [float][days] length of the time interval

**Returns** [list][days] list of times to create scanned intervals

`agis_functions.get_angular_FFOV_PFOV (sat, t)`

Computes angular positions (right ascension  $\alpha$ , declination  $\delta$ ) of the fields of view as a function of time. The angles are as seen from the satellite (Co-Moving Reference System).

**Parameters**

- **sat** – [Satellite object]
- **t** – time at which we want the FoVs pointing directions

**Returns**  $\alpha_{PFoV}, \delta_{PFoV}, \alpha_{FFoV}, \delta_{FFoV}$

`agis_functions.get_basis_Bsplines` (*knots, coeffs, k, obs\_times*)

**Parameters**

- **knots** – [array] knots intervals for the time discretization of the spline (for one (any) of the four quaternions parameters)
- **coeffs** – [array] of the coefficients to create a spline (for one (any) of the four quaternions parameters)
- **k** – [int] spline degree
- **obs\_times** – [list][days] Times of observation

**Returns** arrays of size (#coeffs, #obs\_times)

`agis_functions.get_interesting_days` (*ti, tf, sat, source, zeta\_limit*)

Computes the days in which the Fields of View may see some sources.

**Parameters**

- **ti** – [float] initial time at which we want to evaluate the interesting days
- **tf** – [float] final time
- **sat** – [Satellite object]
- **source** – [Source object]
- **zeta\_limit** – [float][rads] zeta\_limit for the field of view

**Returns** [list of floats] containing the days in which the source may be in the field of view of the telescopes

`agis_functions.get_left_index` (*knots, t, M*)

**Parameters**

- **knots** – knots for the spline
- **t** – [float][days] time at which
- **M** – [int] spline order ( $M=k+1$ )

**Returns** **left\_index** the left\_index corresponding to t i.e.  $i$  s.t.  $t_i < t \leq t_{i+1}$

`agis_functions.get_obs_in_CoMRS` (*source, sat, t*)

Get observation in the Co-Moving Reference System.

**Parameters**

- **source** – [source object]
- **sat** – [Satellite object]
- **t** –

**Returns**  $(\alpha, \delta)$  of the observation in CoMRS

`agis_functions.get_times_in_knot_interval` (*time\_array, knots, index, M*)

**Parameters** **time\_array** – [numpy array]

**Returns** times in knot interval defined by [index, index+M]. I.e. all the times  $t$  such that  $\tau_n < t < \tau_{n+M}$  where **M** is the order of the spline ( $M=k+1$ ) and  $\tau_n$  is the knot number  $n$ .

`agis_functions.multi_compare_attitudes(gaia, Solver, my_times)`

Compares the attitudes in four different plots, one for each attitude component.

**Parameters**

- **gaia** – [satellite object]
- **solver** – [Solver object]
- **my\_times** – [list][days] list of times at which we want to compare the attitudes

**Returns** figure object

`agis_functions.multi_compare_attitudes_errors(gaia, solver, my_times)`

**Parameters**

- **gaia** – [Satellite object]
- **solver** – [Solver object]
- **my\_times** – [list][days] times at which we want to compare the attitudes

**Returns** figure

`agis_functions.observed_field_angles(source, attitude, sat, t, double_telescope=False)`

Ref. Paper [LUDW2011] eq. [12]-[13]

Return field angles according to Lindegren eq. 12. See `compute_field_angles()`

**Parameters**

- **source** – [Source]
- **attitude** – [quaternion] attitude at time t
- **sat** – [Satellite]
- **t** – [float] time at which we want the angles
- **double\_telescope** – [bool] If true, uses the model with two telescopes

**Returns**

- eta: along-scan field angle (== phi if double\_telescope = False)
- zeta: across-scan field angle

`agis_functions.scanning_direction(source, sat, t)`

Computes the y-coordinates of the SRS frame, which is an approximation of the scanning direction. Use for plotting alone

## 4.6 constants.py

**File** constants.py

**Purpose** File containing the constants that will be used in the other files. This will allow to avoid “magic numbers” in the code and also to easily change these constants if we later need them more or less precises

**Author** Luca Zampieri 2018

## CHAPTER 5

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### Known Issues

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Too many to be listed for the moment but we will try to make a good list before Christmas.

Problems in class Satellite:

- Attitude not constructed if `t_init != 0`

---

**Note:** If you find any issue that is not on the list, you can contact us by email and we will: \* Add it to the list \* Try to fix it

---





## Notations

Table 1: Description of the symbols used in the code

Symbol	Description
$\alpha$ or ra	Right ascension
$\delta$ or dec	Declination
$\eta$ or eta	Along-scan field angle see picture
$\zeta$ or zeta	Across-scan field angle see picture

## 6.1 Testing tables

test	Values	Examples	Description
<i>SCI_EXTENSION</i>	integer	2	Index of science extens

Other option Simple table

Inputs		Output
A	B	A or B
False	False	False
True	False	True
False	True	True
True	True	True



## CHAPTER 7

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### Indices and tables

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## Bibliography

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- [Lind2001] Calculating the GAIA nominal scanning Law, L. Lindegren SAG-LL-35 19 february 2001 <http://www.astro.lu.se/~lennart/Astrometry/TN/Gaia-LL-035-20010219-Calculating-the-GAIA-Nominal-Scanning-Law.pdf>



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