Current status of the Adaptive Optics Telemetry standard

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Context

- Leading edge **Adaptive Optics** (AO) systems in ground-based observatories produce vast amounts of **telemetry & control data**, that is either not stored or is **difficult for end-users to have access to**.
  - AO telemetry data has been traditionally seen as “**engineering data**”;
  - Poorly documented.
- Different observatories record data in different ways.
  - Sometimes the data format varies even for the same instruments(!)
- To our knowledge, there has been **no major attempt to establish a consensual data format for AO telemetry** to date.

Motivation

- AO telemetry allows for **use-cases** such as:
  - **Advanced exploitation of scientific data**;
  - **System performance estimation and runtime optimization**;
  - **Instrumental research**.
- Due to its wide applicability, **broadening access** to this data has the potential to change the AO landscape on many fronts.
  - In line with the mission of Opticon-RadioNet Pilot (ORP).
- In other words, AO telemetry should be thought of as a **science product**.

The concept

1. Create a **data model** that can provide a **generalized** representation of an AO system, regardless of:
    - **AO Modes**: SCAO / SLAO / GLAO / MOAO / LTAO / MCAO;
    - **Guide stars**: NGS, Sodium LGS, Rayleigh LGS;
    - **Wavefront Sensors**: Shack-Hartmann or Pyramid;
    - **Wavefront Correctors**: Deformable Mirrors, Tip-tilt Mirrors, Linear Stages;
    - **Loops**: Control loops, Offload loops;
    - **Sampling**: High-frame-rate, low-latency | low-frame-rate, larger latency streams.
2. Write data in a standardized **data exchange format** with a structure and data access that is **consistent across all data producing systems**.
3. Data easily shared with users, **abstracted from instrument details**.

Methodology

- Not realistic to save every single datapoint from every single system, so it is necessary to converge to a subset of useful data.
- We focused on 2 **use-cases** to support (top-down approach).
  - **Atmospheric turbulence parameters estimation**;
  - **Point-spread function reconstruction** (PSF-R).
- But we *also* looked at datasets from existent systems, to ensure we can support what is already being typically saved (bottom-up approach).

Adaptive Optics Telemetry standard (AOT)

- We are developing the **Adaptive Optics Telemetry standard (AOT).**
  - Specification paper submitted to A&A.

Adaptive Optics Telemetry Standard

Design and specification of a novel data exchange format

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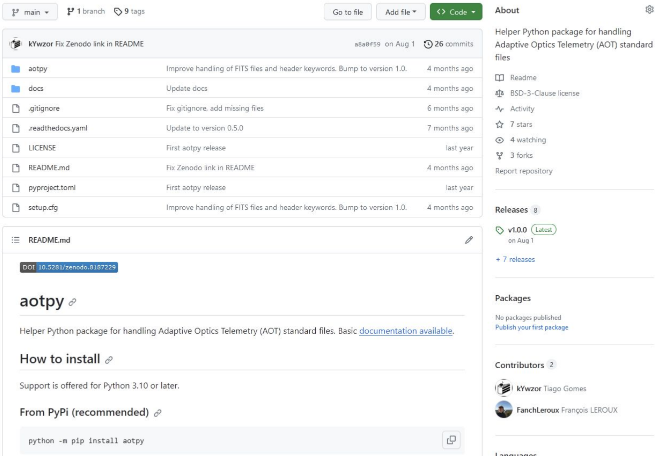
- Based on the Flexible Image Transport System (**FITS**).
- **One file** can contain all relevant AO telemetry data from **one recording**.
  - However, data duplication can be avoided by references to external files (optional).
- Envisioned as a way to **nicely package generated data**.
  - Post-processing step that makes data easier to share and use in pipelines.
  - **Not** designed to replace the real-time recording of instrument data (dumping).

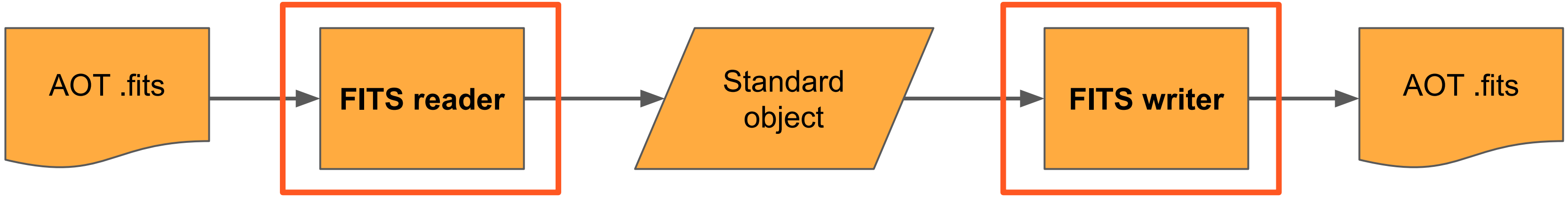
Python Package

Python package

- *aotpy* (Adaptive Optics Telemetry for Python) is an **object-oriented Python package** that supports AOT.
    - Python 3.10+, minimal dependencies (Astropy + Numpy)
- Publicly available on:
    - GitHub: https://github.com/STAR-PORT/aotpy
    - PyPI: https://pypi.org/project/aotpy/ (pip install aotpy)

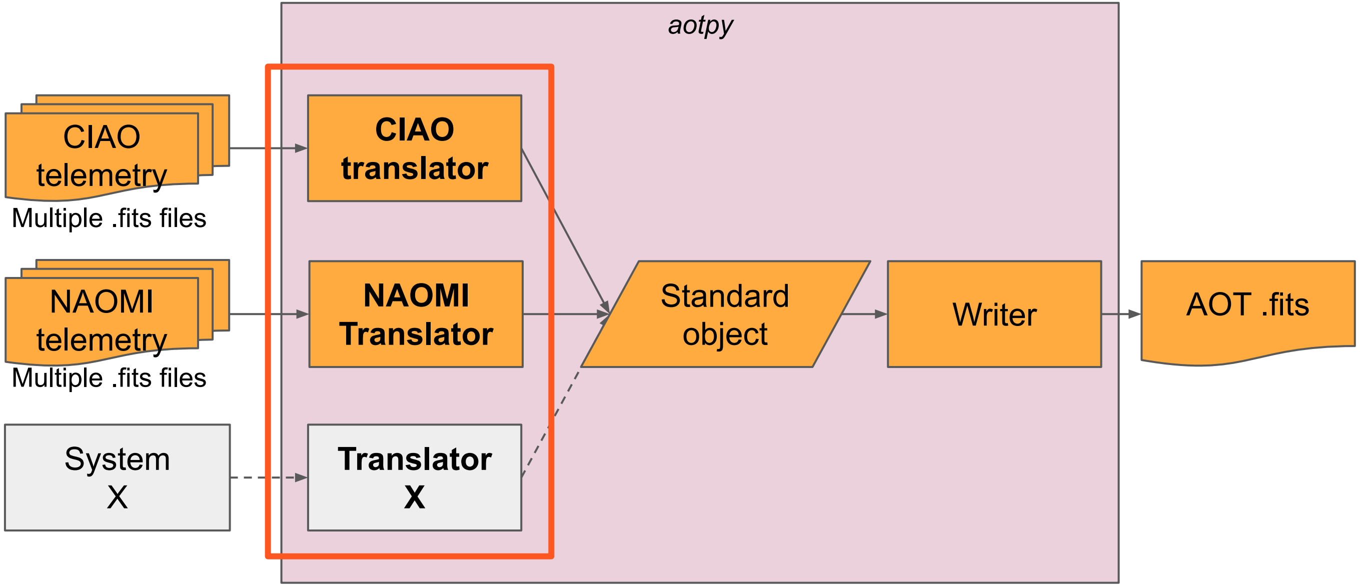


Readers and Writers



- The users are **abstracted from the underlying file handling and structure**.
  - No prior knowledge of the AOT standard is required (interaction through the data model).
- This modular approach allows the standard object to be completely filetype-agnostic.
  - One reader/writer pair for each file type.
  - This means that readers/writers for other file types (such as ASDF or HDF5) **could** be implemented (however, this is **not currently being pursued**).

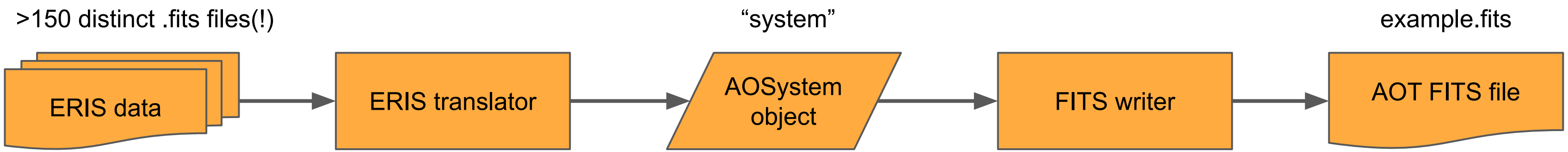
Translators



- These translation scripts allow the user to **work with non-standard data via *aotpy***.
  - **Bridges the gap** for systems that do not make data available in the AOT format.
  - Requires one translator per system we want to support.

Proof-of-concept

Code demonstration




```python
from aotpy.translators import ERISTranslator
system = ERISTranslator('path/to/folder').translate()
system.write_to_file('example.fits')
```

Supported systems and data availability

Source	Instrument	AO mode	WFS config	ESO run
ESO VLT	GALACSI	GLAO/LTAO	5 SHWFS	60.A-9278(B)
ESO VLT	CIAO	SCAO	SHWFS	60.A-9278(C)
ESO VLT	NAOMI	SCAO	SHWFS	60.A-9278(D)
ESO VLT	ERIS	SCAO/SLAO	2 SHWFS	60.A-9278(E)
ALPAO test	PAPYRUS	SCAO	PyWFS / SHWFS	N/A

Proof-of-concept data for all 5 all instruments also available at 10.5281/zenodo.8192741

M	More	HDR	OBJECT	Target Ra, Dec	Program_ID	Instrument	Category	Type	Mode	Dataset ID	Release_Date	TPL ID	TPL START	Exptime
		Header	AO-TELEM	11:09:49.63 -60:30:52.6	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-03-08T05:50:13.153	Mar 8 2019			19.992
		Header	AO-TELEM	11:07:32.53 -59:57:48.6	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-03-08T06:09:23.173	Mar 8 2019			19.992
		Header	AO-TELEM		60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-03-09T21:44:51.082	Mar 9 2019			19.979
		Header	AO-TELEM		60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-03-09T23:24:58.099	Mar 9 2019			19.992
		Header	AO-TELEM	13:57:38.49 -63:41:12.6	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-03-10T07:58:01.328	Mar 10 2019			19.992
		Header	AO-TELEM	13:47:10.50 -62:35:23.0	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-03-10T08:07:01.626	Mar 10 2019			19.992
		Header	AO-TELEM	13:57:38.49 -63:41:12.6	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-03-10T08:15:11.323	Mar 10 2019			19.992
		Header	AO-TELEM	13:57:38.49 -63:41:12.6	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-03-10T08:22:51.420	Mar 10 2019			19.992
		Header	AO-TELEM	15:50:43.34 -53:20:43.4	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-04-0				
		Header	AO-TELEM	15:51:18.51 -53:19:46.3	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-04-0				
		Header	AO-TELEM	15:50:43.34 -53:20:43.4	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-04-0				
		Header	AO-TELEM	15:57:11.80 -53:45:52.0	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-04-0				
		Header	AO-TELEM	17:45:09.03 -33:49:26.3	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-04-0				
		Header	AO-TELEM	17:56:18.25 -33:48:43.2	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-04-0				
		Header	AO-TELEM	17:51:29.26 -34:00:32.9	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-04-0				
		Header	AO-TELEM	17:56:18.25 -33:48:43.2	60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-04-0				
		Header	AO-TELEM		60.A-9278(D)	NAOMI	CALIB	AO-TELEM,AOT,NAOMI	SCAO	NAOMI.2019-04-1				

AO Telemetry Query Form

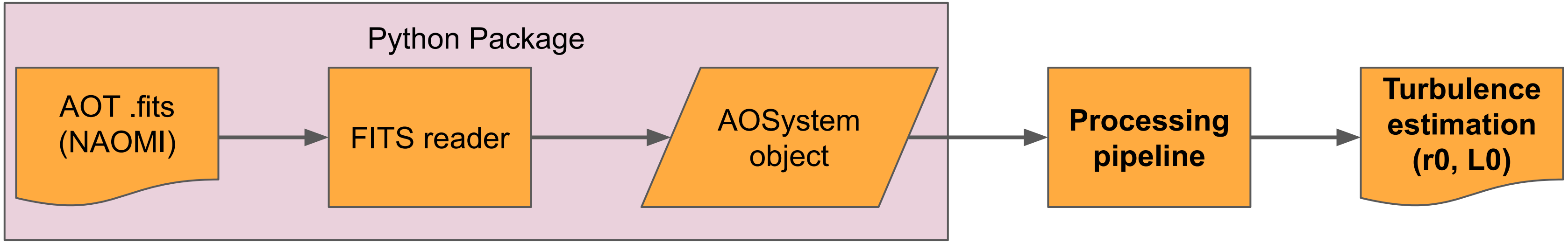
Please enter qualifiers in the fields below and press the '**Search**' button.

Search Reset

- [x] Archive Id...:
- [x] Telescope....:
- [x] Instrument...: Any
- [x] Mjd Obs......:
- [x] Date Obs.....:
- [x] Exptime......:
- [x] Location.....:
- [x] AO Mode......: Any
- [ ] Ins Mode.....: Any
- [ ] Origfile.....:
- [ ] Tel Alt......:
- [ ] Tel Az.......:
- [x] DIMM Seeing:

ESO Archive

Demonstration



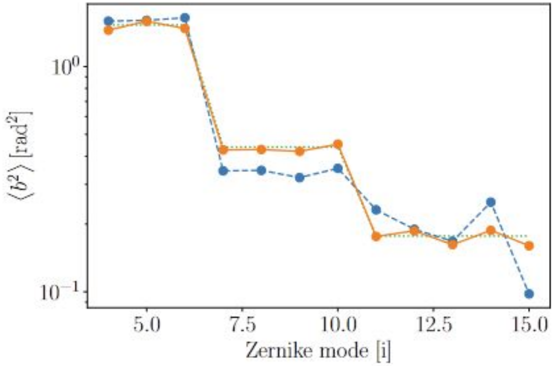
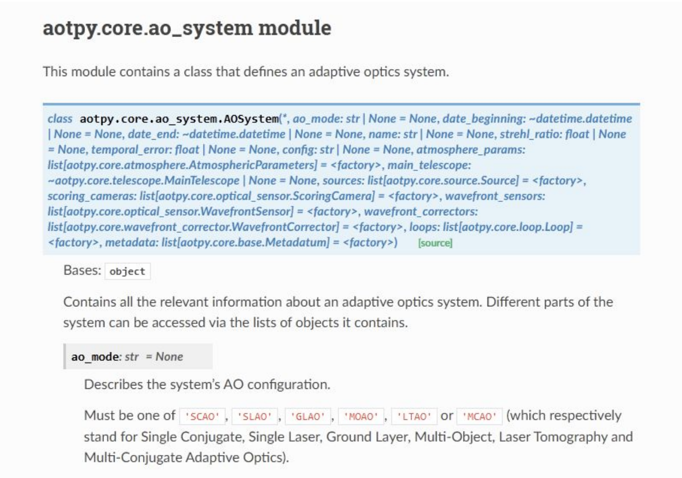


Fig. A.1. In the top graph: (i) the dashed line – the reconstructed variances, $\langle b^2 \rangle$, for a simulated telemetry sample; (ii) the dotted line – the theoretical von Kármán variances of the phase screen turbulence parameters; and (iii) the solid line – the corrected variances.

Turbulence estimation fit utilising telemetry data for the NAOMI system. Source: *Morujão, N. et al. 2023, "Integrated turbulence parameters' estimation from NAOMI adaptive optics telemetry data", A&A, 678, A193*

Future work

- Towards complete post-processing pipelines;
  - Prototype with current telemetry (e.g. ERIS) -> PSF-R;
  - Evaluate adoption for NextGen instruments (e.g. MAVIS);
  - Assist ESO's ELT WG on PSF reconstruction.
- Maturing supporting tools and documentation;
  - Dashboard for exploratory data analysis (Beatriz S);
  - Improve integration with the ESO archive / query forms;
  - Increase database available on ESO archive.
- Exploring and demonstrating the usefulness of AOT in additional scenarios.
  - E.g., AIT phases, ELT-class telescopes, High-Contrast Imaging and Interferometry.



aotpy.core.ao_system module

This module contains a class that defines an adaptive optics system.

class `aotpy.core.ao_system.AOSystem`(**, ao_mode: str | None = None, date_beginning: ~datetime.datetime | None = None, date_end: ~datetime.datetime | None = None, name: str | None = None, strehl_ratio: float | None = None, temporal_error: float | None = None, config: str | None = None, atmosphere_params: list[aotpy.core.atmosphere.AtmosphericParameters] = <factory>, main_telescope: ~aotpy.core.telescope.MainTelescope | None = None, sources: list[aotpy.core.source.Source] = <factory>, scoring_cameras: list[aotpy.core.optical_sensor.ScoringCamera] = <factory>, wavefront_sensors: list[aotpy.core.optical_sensor.WavefrontSensor] = <factory>, wavefront_correctors: list[aotpy.core.wavefront_corrector.WavefrontCorrector] = <factory>, loops: list[aotpy.core.loop.Loop] = <factory>, metadata: list[aotpy.core.base.Metadatum] = <factory>*) [source]

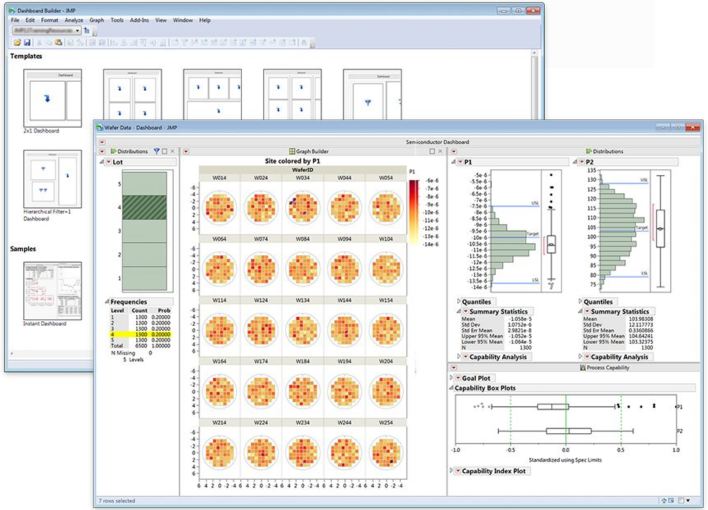
Bases: `object`

Contains all the relevant information about an adaptive optics system. Different parts of the system can be accessed via the lists of objects it contains.

ao_mode: *str* = *None*

Describes the system's AO configuration.

Must be one of `'SCAO'`, `'SLAO'`, `'GLAO'`, `'MOAO'`, `'LTAO'` or `'MCAO'` (which respectively stand for Single Conjugate, Single Laser, Ground Layer, Multi-Object, Laser Tomography and Multi-Conjugate Adaptive Optics).



Thank you

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Extra slides

Data Model

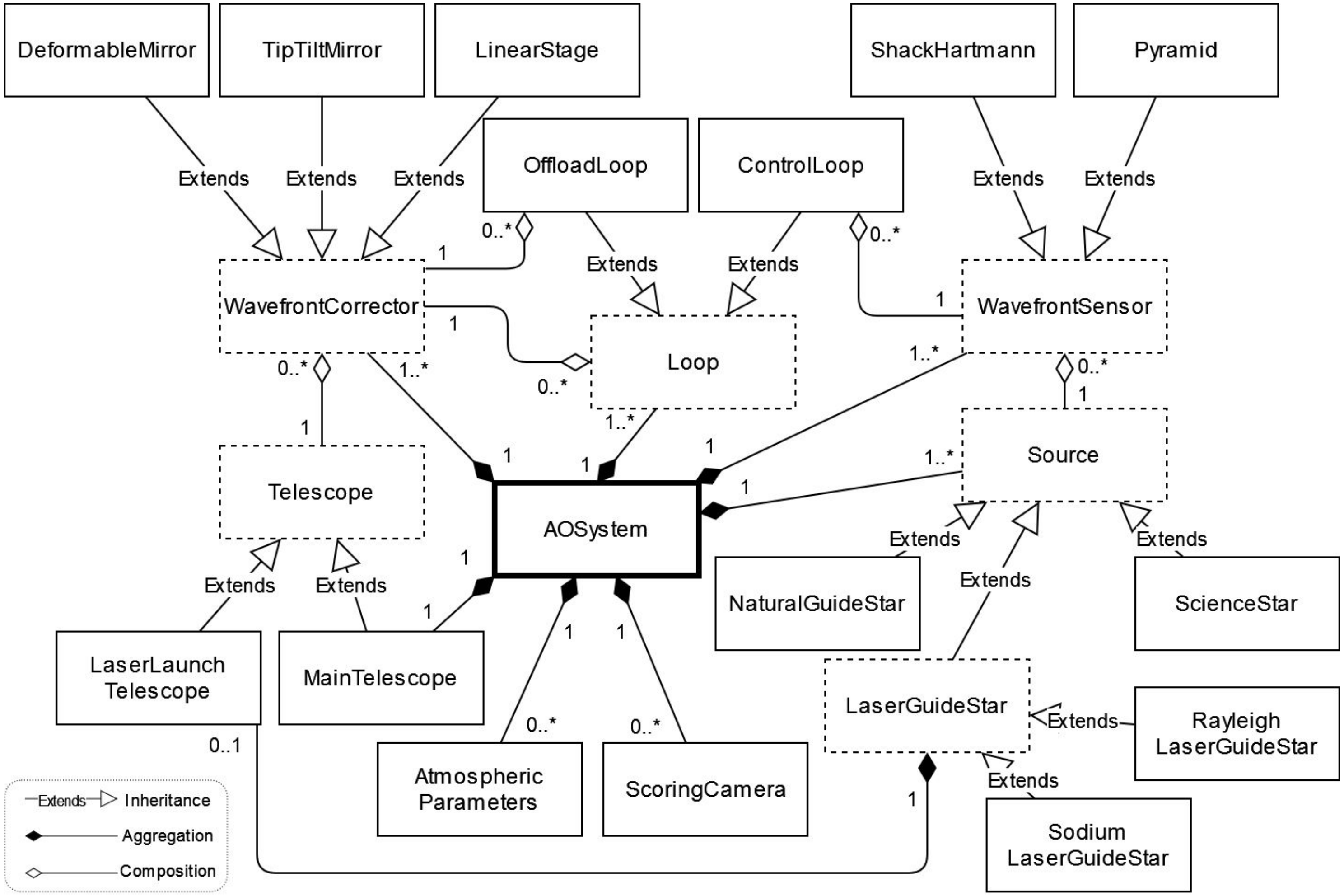
DeformableMirror
TipTiltMirror
LinearStage
ShackHartmann
Pyramid
OffloadLoop
ControlLoop
Extends
WavefrontCorrector
Loop
WavefrontSensor
Telescope
AOSystem
Source
LaserLaunch Telescope
MainTelescope
NaturalGuideStar
ScienceStar
LaserGuideStar
Rayleigh LaserGuideStar
Sodium LaserGuideStar
Atmospheric Parameters
ScoringCamera
0..*
1
1..*
0..1
Extends Inheritance
Aggregation
Composition

Table 11. AOT_WAVEFRONT_SENSORS fields.

Name	Type	Unit	Description
UID	*str*	*n.a.*	Unique ID that identifies the wavefront sensor.[a,b]
TYPE	*str*	*n.a.*	Indicates the type of wavefront sensor (either 'Shack-Hartmann' or 'Pyramid').[a]
SOURCE_UID	*str*	*n.a.*	AOT_SOURCES row-reference. Indicates source being sensed.[a]
DIMENSIONS	*int*	count	Number of dimensions being measured by each subaperture. For 'Shack-Hartmann' this *must* be equal to 2 (horizontal and vertical offset). For 'Pyramid' this *must* be equal to either 2 (if the signals are also interpreted as horizontal and vertical offsets), 1 (if the sub-apertures overlap and are interpreted as a single signal) or the number of sides of the pyramid (that is, N_SIDES signals).[a]
N_VALID_SUBAPERTURES	*int*	count	Number of valid subapertures (*must* coincide with SUBAPERTURE_MASK data).[a]
MEASUREMENTS	*str*	*n.a.*	Image-reference.
REF_MEASUREMENTS	*str*	*n.a.*	Image-reference.
SUBAPERTURE_MASK	*str*	*n.a.*	Image-reference.
MASK_X_OFFSETS	*lst*	pix	List of horizontal offsets in detector pixels. Each offset defines the lowest horizontal position occupied by the respective mask.[c]
MASK_Y_OFFSETS	*lst*	pix	List of vertical offsets in detector pixels. Each offset defines the lowest vertical position occupied by the respective mask.[c]
SUBAPERTURE_SIZE	*flt*	pix	Size of each subaperture in detector pixels.
SUBAPERTURE_INTENSITIES	*str*	*n.a.*	Image-reference.
WAVELENGTH	*flt*	m	Wavelength being sensed.
OPTICAL_GAIN	*str*	*n.a.*	Image-reference.
TRANSFORMATION_MATRIX	*str*	*n.a.*	Image-reference.
DETECTOR_UID	*str*	*n.a.*	AOT_DETECTORS row-reference.
ABERRATION_UID	*str*	*n.a.*	AOT_ABERRATIONS row-reference.
NCPA_UID	*str*	*n.a.*	AOT_ABERRATIONS row-reference, which describes the non-common path aberrations between the wavefront sensor and science detector.

Notes.
(a) Strictly mandatory (value *must not* be null). (b) All entries in this field *must* be unique. (c) For each row in the table, entries in these fields *must* have the same length, equal to the number of masks projected on the detector pixels (there *must* be one mask for 'Shack-Hartmann' and as many as the number of pyramid sides for 'Pyramid').

Example table