Differential Delay Lines

IMT
EPFL
NOVA
ASTRON
MPIA Heidelberg
University of Leiden
Observatoire de Genève

Astrometric Survey for Extra-Solar Planets with PRIMA

PRIMA Astrometry Operations and Software: technical proposal

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	Name	Date	Signature
Prepared	Eric J. Bakker et al.	27 September, 2004	
Approved	Consortium		
Released	Andreas Quirrenbach, Didier Queloz, Thomas Henning		

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Executive summary

This proposal describes the Astrometry Operations and Software component of the PRIMA Differential Delay Lines / Astrometry Operations and Software project. It specifies the deliverables to ESO necessary to operate PRIMA in its astrometric mode, and to reduce the data to an astrometric accuracy of 10 micro-arcseconds. An accuracy of this order is required for astrometric detection of extrasolar planets.

Astrometric observations with interferometers are equivalent to measurements of delays, i.e., to measurements of the difference in optical path length of light from a star at infinity to the two telescopes forming the interferometer. For a 200 m baseline, an accuracy goal of $10\,\mu\text{as} = 50$ picorad obviously corresponds to a total allowable error of 10 nm. This stunning accuracy can only be achieved through a triple-differential technique:

1. Two stars with small angular separation are observed simultaneously to reduce the effects of atmospheric turbulence.

2. The optical pathlength within the interferometer is monitored with a laser interferometer. The terms entering the error budgets (e.g., due to small movements of mirrors, or variations of the air pressure in the delay line tunnels) are thus the differential effects of changes within the interferometer on the starlight and metrology beams.

3. The orbits of extrasolar planets are determined from variations of the positions of their parent stars with time, measured with respect to one or several reference stars.

The implementation of this triple-differential technique requires unusual attention to detail in the understanding of varied astrophysical, atmospheric, and instrumental effects, in the construction of error budgets, in planning the operations, and in specifying and coding the data reduction software.

In particular, the desired accuracy can only be achieved if all systematic error sources that can possibly affect the data are understood properly, and removed in a systematic way. While the magnitude of some astrometric errors can be predicted quite reliably (e.g., those related to atmospheric turbulence), others defy simple analysis and may have to be described with parameterized models (e.g., dynamic temperature gradients in the VLTI light ducts). Experience with other forefront astrometric facilities (the HIPPARCOS spacecraft, the Mark III Interferometer, the automated Carlsberg Meridian Circle) also shows that completely unanticipated systematic effects almost inevitably show up in the actual data. The ability to detect, diagnose, and remove such unanticipated effects is of paramount importance for the success of astrometric programs.

This proposal is therefore devoted to the a priori analysis of the errors relevant for the astrometric mode of PRIMA, and to the design and implementation of systems for a posteriori analysis of remaining trends in the data. We propose to deliver a formal astrometric error budget analysis, alongside with suggestions to ESO on how to mitigate adverse effects of environmental influences such as thermal loads on the light ducts. We will further deliver an calibration and observation strategy that will take full advantage of, and optimize use of, the triple-differential technique described above. We will finally deliver software to perform the initial steps of the data reduction, including carrying out said differences with appropriate corrections, and conversion of delays to angles on the sky. Our data reduction software will allow inspection of the residuals and enable searches for remaining systematic trends.

The intention of the present proposal is thus to design, create and provide a system which enables all astronomers, both within and external to the proposing consortium, to obtain calibration solutions for their scientific data sets required to perform astrometric measurements with the maximum accuracy attainable with PRIMA. The scope of the proposed deliverables to ESO has been guided by the principle that the consortium should provide tools necessary for the full exploitation of the astrometric mode of PRIMA by the ESO users community.

To this end, three categories of deliverables are identified:

PRIMA astrometry error budget, calibration and observation strategy: These two deliverables have the specific intent to quantify all expected systematic error sources, to identify techniques to minimize the impact of these sources (i.e., hardware, software, calibration), and to propose a calibration and observation strategy which will minimize the impact of these errors.

PRIMA astrometry observing preparation tools: Two tools will be required to prepare astrometric observations: one that allows to identify those dates and time of observations which yield the most stringent constraints on astrometric parameters (such as orbital elements of a planetary companion), and one that calculates the exposure time. For both tools, the consortium will develop the algorithms.

PRIMA astrometry reduction library: A library of routines will be developed that allows to determine the optimal calibration solution from a large set of data, and to apply this solution within the ESO pipeline to an individual observation to obtain calibrated PRIMA astrometry data. The data reduction library will provide the functionality required for identifying and removing systematic trends in the data.

Chapter 1

Introduction

1.1 Scope

The scope of this document is to specify operational aspects and software efforts in relation to the PRIMA Astrometric Planet Search Program. These efforts are part of a proposal by a Dutch/German/Swiss consortium to:

1. To build four PRIMA differential delay lines (DDL);
2. Deliver the PRIMA astrometric operations and software package (this proposal);
3. Execute the planet search program within the guaranteed time program (GTO).

A detailed description is given on the difficulties expected for operating PRIMA to the micro-arcsecond astrometry level (PRIMA error budget, calibration and observation strategy), reducing the PRIMA astrometry data in a self-consistent manner, and to develop the observation preparation tools necessary to conduct a research program. The document has the purpose to be a framework for the consortium and ESO on the scope of the Astrometric Operations and Software (AOS) activities within the consortium. It specifies deliverables included in the project plan, and list some items that are explicitly excluded. It specifies what will be delivered at which occasion. This document serves to inform the ESO VLTI team, ESO council, and ESO STC on the intentions of the consortium.

This proposal is an answer to and compliant with the Statement of Work and the VLT Data Flow Requirements (AD-1 and AD-2).

1.1.1 Contributions to document

The people who have contributed to this document are among others:

1. NOVA/Leiden Observatory:
    - Andreas Quirrenbach;
    - Walter Jaffe;
    - Rudolf Le Poole;
    - Bob Tubbs;

- Jeroen de Jong;
- Sabine Frink;
- Saskia Hekker;
- Simon Albrecht;
- Eric J. Bakker.

2. Geneva Observatory:
   - Francesco Pepe;
   - Didier Queloz;
   - Damien Ségransan;
   - Danuta Sosnowska.
3. MPIA at Heidelberg
   - Thomas Henning;
   - Ralf Launhardt;
   - Johny Setiawan.
4. ASTRON:
   - Lars Venema;
   - Koji Murakawa.
5. JIVE:
   - Huib Jan van Langevelde.
6. This document has been discussed with ESO at several occasions, and suggestions for improvements have been incorporated in this document:
   - Frédéric Derie;
   - Françoise Delplancke;
   - Pascal Ballester;
   - Andreas Glindemann;
   - Guy Monnet;
   - Isabelle Percheron.

1.2 Documents

1.2.1 Applicable documents

The following documents, of the exact issue shown, form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the content of this specification, the content of the specification shall be considered a superseding requirement.

AD-1	Data Flow for VLT/VLTI Instruments Deliverables Specification	VLT-SPE-ESO-19000-1618	Issue 2.0	2004-05-22
AD-2	Statement Of Work for PRIMA DDL System	VLT-SOW-ESO-15720-2304	Issue 2.0	2004-02-12
AD-3	Statement of Work for PRIMA astrometric operation and software	VLT-SOW-ESO-15750-3298	Issue 2.0	2004-06-23
AD-4	Software Management Plan	VLT-PLA-ESO-00000-0006	Issue 2.0	1992-05-21
AD-5	Standard Procedures for Design Review	VLT-INS-ESO-00000-0251	Issue 2.0	1993-02-22
AD-6	Documentation Plan	VLT-PLA-ESO-00000-0005	Issue 2.0	2000-09-14
AD-7	Configuration Control Plan	VLT-PLA-ESO-00000-0002	Issue 1.0	1991-04-25
AD-8	Management Plan	VLT-PLA-DDL-15720-0001	Issue 3.0	2004-03-08
AD-9	Project Plan	VLT-PLA-DDL-15720-0002	Issue 3.0	2004-03-17
AD-10	RIXs relative to PRIMA Astrometry Operations and Software - Technical Proposal	TSD-04/036		2004-04-27

1.2.2 Reference documents

RD-1	PRIMA DDL Performance and Technical Requirement Specifications	VLT-SPE-ESO-15720-2209	Issue 1.0	2000-10-30
RD-2	VLTI Software Requirements on Data Flow System	VLT-SPE-ESO-15000-2564	Issue 2.0	2001-9-2
RD-3	Executive Summary of the Proposal	PLANETS-PRI-ESU-0000	Issue 1.0	2003-10-23
RD-4	Scientific Proposal	PLANETS-PRI-SCI-0001	Issue 1.0	2003-10-23
RD-5	DDL Technical Proposal	PLANETS-PRI-TEC-0002	Issue 1.0	2003-10-23

1.2.3 Document organization

This document is structured around three categories of deliverables:

- PRIMA astrometry error budget, calibration and observation strategy
- PRIMA astrometry observation preparation tools
- PRIMA astrometry data reduction library

Each of these deliverables is described briefly, and if needed, additional information on each deliverables is available in the Appendix.

1.3 Acronyms

AD	Applicable Document
AOS	Astrometry Operations and Software
API	Application Programmer Interface
AT	Auxiliary Telescope
CASE	Computer Aided Software Engineering
CDR	Conceptional Design Review
COM	Commissioning
DAF	Data Analysis Facility
DICD	Data Interface Control Document
DICB	Data Interface Control Board
DDL	Differential Delay Line
DRS	Data Reduction Software
ESO	European Southern Observatory
ETC	Exposure Time Calculator
FAC	Final Acceptance Chili
FAE	Final Acceptance Europe
FAR	Final Acceptance Review
FDR	Final Design Review
FSU	Fringe Sensor Unit
FTE	Full-Time Equivalent
GTO	Guaranteed Science Observations
GUI	Graphical User Interface
HW	Hardware
ICD	Interface Control Document
IDAF	Interactive Data Analysis Facility
IDE	Integrated Development Environment
IRR	Integrated Readiness Review
ISS	Interferometric Supervisor Software
KO	Kick-off
MACAO	Multi Application Curvature Adaptive Optics
MAIV	Manufacture, Assembly, Integration, and Verification
MET	Metrology
MoU	Memorandum of Understanding
NEVEC	NOVA ESO VLTI Expertise Center
NPOI	Naval Prototype Optical Interferometer
OO	Object Oriented
OB	Observation Block
OPD	Optical Path Difference
OS	Observation Software
PA	Position Angle
PAC	Provisional Acceptance Chile
PAE	Provisional Acceptance Europe
PAOS	PRIMA Astrometry Operations and Software
PDR	Preliminary Design Review
PRIMA	Phase Referenced Imaging and Microarcsecond Astrometry
PS	Primary Star
RD	Reference Document
SES	Secondary Star

SIM	Space Interferometry Mission
STS	Star Separator
SQL	Standard Query Language
SW	Software
TBD	To Be Determined
TRR	Test Readiness Review
UML	Unified Modelling Language
USNO	United States Naval Observatory
VLBI	Very Large Baseline Interferometry
VLT	Very Large Telescope
VLTI	Very Large Telescope Interferometer

Chapter 2

Project description

2.1 Science drivers

The science goals of the Consortium are twofold:

1. Accurate measurement of the mass and orbital parameters of extrasolar planets detected by radial-velocity surveys;
2. Planet search covering previously uncovered parameter space along the main sequence and in time.

The technical work performed by the Consortium will also enable research in areas that are not directly related to the Consortium's own scientific goals. Examples of additional important science goals of the PRIMA astrometric facility are:

1. Motions of stars: e.g. in clusters, the Galactic Center;
2. Orbital motion of stars due to e.g. binarity;
3. Gravitational micro-lensing.

Studies have demonstrated that the science drivers and exciting science goals for the astrometric mode of PRIMA can only be attained if PRIMA is able to reach an astrometric accuracy of about 10 micro-arcseconds (see also Figure 2.1). In order for PRIMA to reach this accuracy, the Consortium has identified two critical elements:

1. PRIMA differential delay lines;
2. PRIMA astrometric operations and software (which includes an in-depth analysis of the PRIMA astrometry error budget, calibration and observation strategy, observation preparation tools, and a uniform calibration of the data for the whole duration of the science program).

By providing these critical elements, the Consortium intends to help ESO implement the full astrometric capability of the PRIMA foreseen in ESO's PRIMA development plan, on a time scale that is scientifically attractive and competitive.

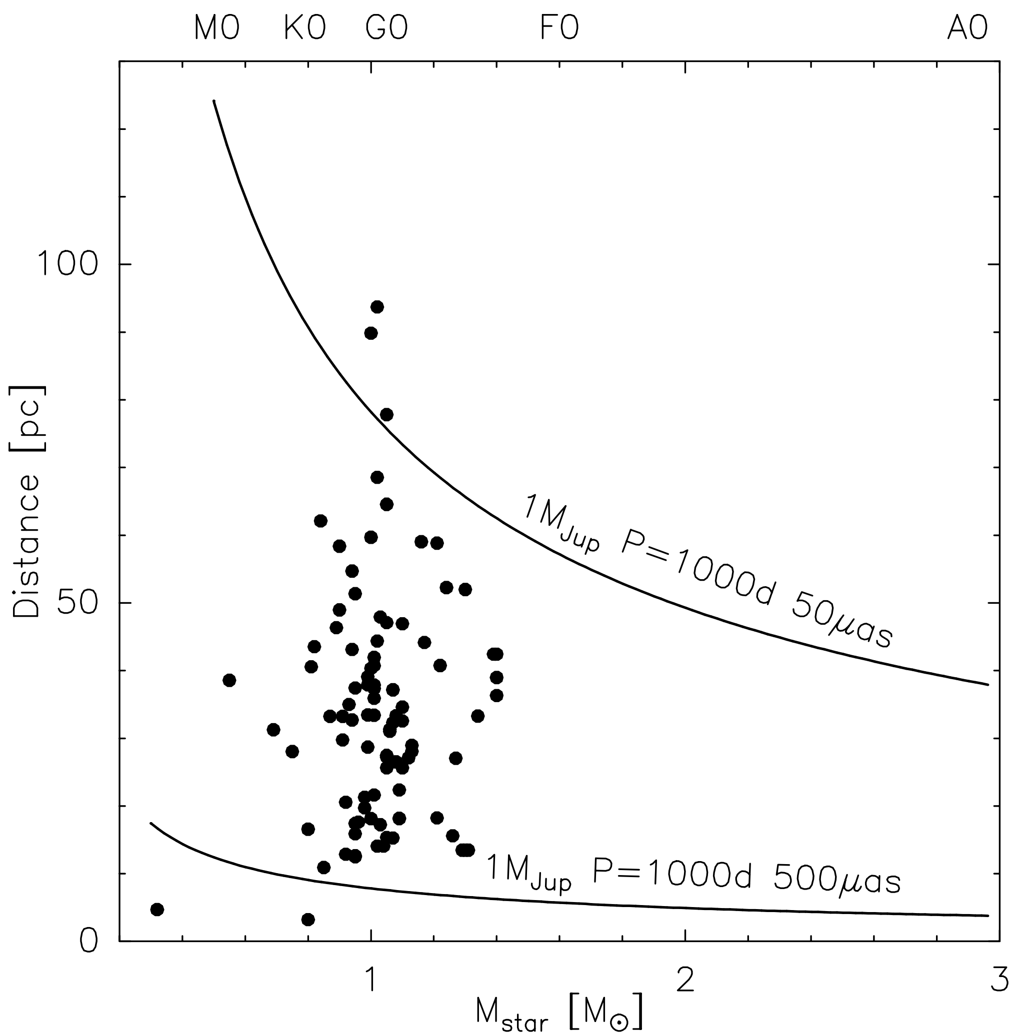

Figure 2.1: Graph showing the dramatic drop in accessible planetary system with a decrease of astrometric accuracy.

2.2 Measurement principle and high-level instrumental requirements

2.2.1 Atmospheric limitations of astrometry

Astrometric observations from the ground are fundamentally limited by the Earth's atmosphere, which gives rise to *image motion* with a typical amplitude of $0\farcs5$. This makes absolute astrometry with milli-arcsecond precision extremely difficult. Over small angles on the sky, image motion is highly correlated, however; this makes much more precise *differential* positional measurements between objects in the same field possible. The atmospheric error of astrometric measurements with a long-baseline interferometer scales linearly with the separation of the target from the chosen reference star, and with the $-2/3$ power of the baseline length. For typical atmospheric conditions at a good site such as Cerro Paranal, an interferometer with a 100 m baseline can achieve $\sim 10\,\mu$as precision over a $10''$ arc with a half-hour integration time. The high-level specification for the astrometric mode of PRIMA is derived from this fundamental atmospheric limit, i.e., with $10\,\mu$as instrumental errors, the performance of PRIMA will not be limited by the facility, but rather by the Earth's atmosphere.

2.2.2 Dual-star interferometry

In a dual-star interferometer such as PRIMA, each telescope accepts two small fields and sends two separate beams through the delay lines. The delay difference between the two fields is taken out with an additional short-stroke differential delay line. An internal end-to-end laser metrology system is used to monitor the delay difference within the interferometer $\Delta D_{\rm int}$. If the external delay difference D is equal to the internal delay for both target and reference, the zero-order fringe is observed in both fringe sensing units. Otherwise, the delay offset has to be estimated from the fringe data, and

$$\Delta D = \Delta D_{\rm int} + D_{\rm FSU1} - D_{\rm FSU2} \quad . \tag{2.1}$$

For astrometric observations, this delay difference ΔD is the observable of interest, because it is directly related to the coordinate difference between the target (subscript t) and reference stars (subscript r):

$$\Delta D \equiv D_t - D_r = \vec{B} \cdot (\hat{s}_t - \hat{s}_r) = B(\cos\theta_t - \cos\theta_r) \quad . \tag{2.2}$$

Here $\hat{s}$ denotes the unit vector in the direction of the star, and θ can be interpreted as a one-dimensional measurement of the position of the star.

2.2.3 Precision requirements

The fundamental instrumental requirements can be derived directly from Eqn. 2.2, which can be written as

$$\Delta D \equiv D_t - D_r = \vec{B} \cdot (\hat{s}_t - \hat{s}_r) \equiv \vec{B} \cdot \Delta\vec{s} \quad . \tag{2.3}$$

The propagation of systematic errors in measurements of the differential delay $\delta\Delta D$ and of the baseline vector δB to errors in the derived position difference $\delta\Delta s$ can be estimated from the total differential

$$\delta\Delta s \approx \frac{\delta\Delta D}{B} + \frac{\Delta D}{B^2}\delta B = \frac{\delta\Delta D}{B} + \Delta s\frac{\delta B}{B} \quad . \tag{2.4}$$

For a $5\,\mu$as (25 prad) contribution to the error budget for measurements with a 200 m baseline, the metrology system must thus achieve a precision $\delta\Delta D = 5$ nm; *the delay measurements have* *eleven significant digits*. Likewise, the fringe sensing units must deliver data that allow estimation of the delay to this precision, which corresponds to measuring the fringe phase to $\sim 0.015\,\mathrm{rad}$, for observations in the K band. Fortunately, the relative error of the baseline vector gets multiplied with Δs; this means that the baseline vector has to be known to $\delta B \approx 50\,\mu\mathrm{m}$.

2.2.4 Parallax, proper motion, and astrometric planet searches

Observing the astrometric wobble due to a planetary companion means measuring the variation of the stellar position over time. Superimposed on this signal – which has a typical amplitude of a few tens of micro-arcseconds – are the parallax and stellar proper motion, which have typical values of order tens to hundreds of milli-arcseconds (mas/yr, respectively). Since parallaxes and proper motions are never known with the required precision, they must be determined from the data.[1] The stellar trajectory in the absence of planets can be described *exactly* by five free parameters (two-dimensional position, two-dimensional proper motion, parallax);[2] therefore residuals after fitting these parameters are sensitive indicators for disturbances. Although the size of parallax and proper motion is four order of magnitudes larger than the planetary signatures we are looking for, the residuals can therefore be interpreted reliably.

It is important to realize that the measurement principle draws heavily on *differential methods* to eliminate atmospheric, instrumental, and astrophysical effects that are many orders of magnitude larger than the intended measurement precision:

1. Image motion induced by the atmosphere is limited by the dual-star method, which measures the delay *difference* between the target and a nearby reference star.

2. Instrumental variations are monitored by an internal laser interferometer, such that only the optical pathlength *difference* between the metrology beam and the starlight beam enters into the error budget.

3. The planetary signature is the *difference* of the observed trajectory from a best-fit five-parameter standard astrometric model.

2.2.5 Implications for data reduction strategy

To summarize, the data from astrometric observations with PRIMA will have unique properties, due to the measurement principle inherent in differential astrometry:

1. PRIMA will make *triple differential* measurements.

2. The elementary data are delay measurements *with eleven significant digits*.

3. The elementary delay measurements are themselves derived from multiple inputs, which are generated by different PRIMA subsystems (chiefly the two fringe sensing units and the end-to-end metrology).

[1] Technically speaking, we are dealing with *relative* parallaxes and proper motions between the target and reference stars.

[2] For nearby stars, perspective acceleration is also significant, but this effect can be predicted precisely if the radial velocity is also known.

4. The data have to be corrected for systematic astrophysical effects (parallax and proper motion) with amplitudes *four orders of magnitude* larger than the required accuracy; parallax has natural time scale of 1 year.

These characteristics call for a more systematic approach to data reduction than is usually applied to other instruments; the PRIMA astrometry data will have to be reduced in a self-consistent manner over several years. To realize this, the Consortium is proposing the Data Analysis Facility (IDAF). Benefits of a consistent comprehensive approach to data reduction will be:

1. *Verification of the instrumental performance.* Since intermediate data products do not have a meaning at the desired level of precision, the only way to verify the instrumental performance is to check whether the residuals after the five-parameter astrometric fit have the expected 10 μas standard deviation;

2. *Diagnosis and removal of systematic errors.* Analysis of the dependence of the residuals on observing parameters or environmental variables (zenith angle, delay line position, outside temperature, humidity, ...) may reveal systematic trends. Empirical parameterized fits of such trends can improve the data quality; systematic trends may also point towards problems in the hardware that need to be fixed;

3. *Traceability of the calibration for multi-year data sets.* Improved calibration procedures can easily be applied consistently to all data taken for a specific project.

2.3 Definition of astrometric data

The final science product of an astrometric observation is the angular offset vector between primary (PS) and secondary (SES) star projected on the baseline (i.e., the offset in arc-seconds and the P.A. of the baseline vector in deg), and its error. This quantity has to be calculated by the observer (or the pipeline) from the total differential OPD of the two stars (plus error) and the baseline vector (plus error). The baseline solution has to be calculated off-line from dedicated observations of a selected set of stars with known absolute positions. After zero OPD calibration (between two telescopes), the total differential OPD between PS and SES is composed of

1. The internal differential OPD (in nm, from metrology);

2. The residual differential OPD (from FSUs, if fringes are not centered perfectly);

3. The residual differential atmospheric OPD (assumed to average out).

1 (and 2) are the data products of an astrometric observation (i.e., the observables) that are directly related to the science product. Both the baseline solution and the differential OPD have several sources of error, both stochastic and systematic, predictable and non-predictable, all with different time scales. They have to be calibrated from a set of data and parameters that are obtained from dedicated calibration measurements as well as from each science observation.

To calibrate effects with time scales longer than an observation (trends), all data obtained within a given period (months to years) have to be included to arrive at a consistent global solution and optimized calibration parameters. Specifically, only one global solution will be derived for all astrometric programs, and that all this data should be available to compute the calibration solution.

these calibration data should be stored in separate files that are accessible to all observers. Otherwise, observers with small programs could not calibrate their data as good as observers with large programs (i.e., with many observations).

We adopt that PRIMA astrometric data has the following characteristics:

1. It is the projected angular separation scalar between two sources (separation vector projected on the baseline vector);
2. It is a time series of calibrated astrometric data (possibly as long as the duration of science operations of PRIMA).

2.4 Observation preparation tools

At least two tools will need to be developed to prepare observations with PRIMA in astrometry mode. The first tool is concerned with the predictions of the astrometric angle between the science and reference star for a given date, with give the possibility to schedule observations at a preferred epoch to optimize the constrain on the orbital parameters. The second tool in the observation preparation toolbox is the exposure time calculator. The latter will have to take into account the change of baseline during an exposure and the atmospheric seeing conditions.

2.5 Error budget, calibration and observation strategy

The Consortiums science goals require an astrometric accuracy of 10-micro-arcseconds. Although ESO has specified the subsystems of PRIMA consistently with a $10\,\mu$as astrometric precision. no formal error budget that includes all external (atmospheric, astrophysical, calibration) errors has yet been constructed. This error budget forms the basis of the formulation of calibration and observation strategy, and for the specification of the PRIMA data reduction library and data analysis facility.

The error budget is the high-level tool to analyze the performance of PRIMA, to specify the requirements for its subcomponents and for data reduction tools, and to define the calibration and observing procedures. The error budget provides the metrics against which to verify the as-built performance of all components and procedures of the astrometric facility.

2.6 Astrometric data reduction, calibration, analysis and trending

From experience from other astrometric instruments (HIPPARCOS, FK5, SIC, NPOI, etc.) we have learned that the observation strategy and the data reduction process play a very significant role, comparable to the hardware, in reaching the science goals of these instruments/facilities. One of the key studies included in this project is a full analysis of the overall PRIMA astrometric error tree and a strategy on how to minimize the impact of the error on the final astrometric parameters. This must be realized through a combination of an advanced observation strategy, calibration strategy, and a sophisticated data reduction process.

An assessment must be made to decide which of the error terms are really significant (in most cases this will not be possible until the design and performance of the star separator, fringe sensor unit, differential delay lines, metrology system etc. have been determined). When this has been done,

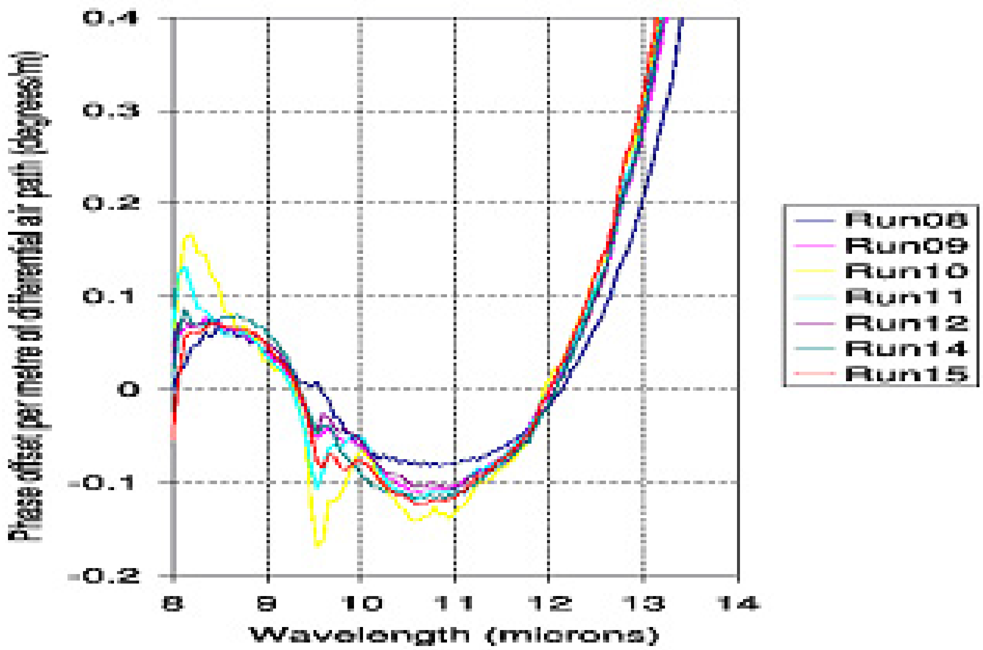

Figure 2.2: Effects of differential phase due to air in the delay line tunnel as measured with MIDI.

the effect of many of the remaining error terms will only be understood through the design of a calibration and observation strategy which allows measurement of the dependence of the error on its cause, and through the design of software which can analyze this cause-and-effect relationship. Many of the errors vary on month timescales or depend on several input variables, so we will need many months of data to separate the different effects. Appendix A gives an overview of a very preliminary error tree.

An example of an entry in the error tree is to correct for the pathlength difference between the 1.7 micron metrology beam and the 2.2 micron science beam, due to dispersion in the VLTI feed system and delay lines, and to beam walk on the various surfaces in the optical train. We have some experience of these differential phase measurements with MIDI now (see Figure 2.2). The runs shown took place on one night (13 June 2003) and it is clear that the differential phase varied continuously during the night. By making several such measurements on nights when the humidity is going up/down, the temperature is going up/down, the pressure is going up/down, the star is increasing in elevation etc. it should be possible is work out what is causing this effect. A similar process will be required for PRIMA, and will require comparisons of observations on a large number of nights.

Data reduction software tools to process the data to science grade results, and analyze the data to facilitate interpretation. Based on experience with other astrometric facilities (Geodetic VLBI (JIVE, Langevelde), HIPPARCOS (Leiden, Le Poole), SIM (Leiden, Quirrenbach), NPOI (ESO, Hummel), Astrometry based on astrographic catalogs (e.g. at USNO, FK5)) the calibration of the data to an accuracy of 10 micro-arcseconds for the duration of science operations of the PRIMA astrometric facility will require to correct the data for trends and variations superimposed on the science parameters. Some of these trends are not well understood, some of them are unknown, and some of them are known at this stage. It is the Consortiums view, that calibrating of the data for the duration of science operations on PRIMA, is not a task for individual astronomers. It is too complex for an individual astronomer and hence PRIMA astrometry would not become an instrument for main stream astronomy.

The Consortium proposes that PRIMA astrometric data is reduced as a uniform data set, systematic errors due to long-term trends are identified and removed. To reach these objectives four phases of data reduction are foreseen (Table 2.1).

Phase	What	Output	How	Where	Who
Pipeline	One Observation Block	Rough projected astrometric data on nominal baseline	NI	On-P	ESO
Nightly	One nights of data	Updated solution for the baseline for that night and updated astrometric data for that night	NI	On-P	ESO
Global (IDAF)	Several years of data	Calibration engine/matrix and science grade astrometric data	I	Off-E	Consortium
Global (DAF)	Any exposure in archive	Science grade astrometric data with the latest calibration engine/matrix	NI	Off-E	ESO

How: Non-interactive (NI) or Interactive (I)
Where: Online at Paranal (On-P), Off-line Europe (Off-E)

Table 2.1: Definition of four phases of data reduction for PRIMA astrometry.

The pipeline reduction phase and the nightly reduction of PRIMA astrometry data at Paranal will be under the responsibility of ESO. The global reduction of all data available to the Consortium will be under the responsibility of the Consortium for the duration of the contract. Based on the available data to the Consortium, a calibration engine will be developed which would allow calibration of any (scientific valid) exposure present within the archive. However the calibration engine will be less accurate if the observation parameters are different than those on which the calibration engine has been based. The Consortium will provide the calibration engine to ESO, after which ESO has the capability to reduce and calibrate the data not available to the Consortium (the usual practice) for astronomers not part of the Consortium. For further details see Section 3.5.16. An updated calibration engine will be provided by the Consortium to ESO on a regular basis (e.g. every six month, to be negotiated) or whenever the new calibration solution provides superior results than the previous solution.

At this stage it is practically impossible to assess the magnitude of each expected error source, nor is it impossible to compile a complete list of error sources. The remedy we propose is a full analysis of a large set of astrometric observations, and a posteriori elaboration of independent variables (and approach previously applied for e.g. independent rotations of the HIPPARCOS grid for the two viewing directions, scale variation of mountain-top with seasonal temperature (Mark III), coal loading of Leiden observatory during the winter season, stratification of air inside the telescope of the automated Carlsberg Meridian Circle).

To identify such trends and the correct these trends an interactive data analysis facility is required, which is the interactive analogue to the ESO pipeline, with some additional data analysis functionality.

The data reduction philosophy is that the IDAF will allow to interactively identify trends from know and unknown error sources. A calibration engine will be developed that has a hard-coded algorithms to correct for each trend, either individually, or in some complex combination. The calibration engine generates for each observation (for which data is accessible) a calibration matrix which specifies the error terms for that particular observation. The calibration matrix in combination with the non-interactive pipeline, generates science grade data from the raw data files. To calibrate observations of which the data is not accessible by the IDAF, the calibration engine will make an calibration based on interpolation.

Chapter 3

Deliverables and tasks

3.1 Overview of deliverables

Three categories of deliverables are identified:

PRIMA astrometry error budget, calibration and observation strategy:
PRIMA astrometry error budget
PRIMA astrometry calibration and observation strategy
PRIMA astrometry observation preparation tools:
PRIMA astrometry angle calculator
PRIMA astrometry exposure time calculator
PRIMA astrometry data reduction library
PRIMA astrometry data reduction library

For each category Tables 3.1, 3.2, 3.3 and 3.4 specifies in some more details individual documents, library modules etc. as deliverable. The following milestones have been defined for the PRIMA DDL project:

CDR: Conceptual Design Review (internal)

PDR: Preliminary Design Review

FDR: Final Design Review

IRR: Integration Readiness Review (internal)

PAE: Preliminary Acceptance Europe

COM: Instrument Commissioning

PAC: Preliminary Acceptance Chile

	CDR	PDR	FDR	IRR	PAE	COM	PAC	FAR
PRIMA astrometry error budget, calibration and observation strategy								
PRIMA astrometry error budget	Iss.0	Iss.1	Iss.2		Iss.3			Iss.4
PRIMA astrometry calibration and observation strategy	Iss.0	Iss.0.1	Iss.1		Iss.2			
PRIMA astrometry calibration and observation plan	Iss.0	Iss.0.1			Iss.2			
Requirements on PRIMA astrometry templates		Iss.1	Iss.2					
Requirements on PRIMA astrometry calibrators		Iss.1	Iss.2					
Requirements on PRIMA astrometry reference sources		Iss.1	Iss.2					
List and details on astrometry calibrators					Iss.1			

Documents with issue 0 refer to a draft. Software with version 0 refer to a beta release.

Table 3.1: Detailed overview of deliverables "PRIMA astrometry error budget, calibration and observation strategy".

	CDR	PDR	FDR	IRR	PAE	COM	PAC	FAR
PRIMA astrometry observation preparation tools								
Requirement on observation preparation tools	Iss.0	Iss.1						
Performance verification matrix		Iss.0	Iss.1					
Functional specifications of the observation preparation tools		Iss.1						
Design of observation preparation tools			Iss.1					
Prototype of critical modules			v0.1					
Library and documentation of observation preparation tools					v1.0		v1.x	
Demonstration				demo				
On-site implementation plan of observation preparation tools					Iss.1		Iss.1.x	
User manual of observation preparation tools					Iss.1		Iss.1.x	
Maintenance manual of observation preparation tools					Iss.1			

Documents with issue 0 refer to a draft. Software with version 0 refer to a beta release.

Table 3.2: Detailed overview of deliverables "PRIMA astrometry observation preparation tools".

	CDR	PDR	FDR	IRR	PAE	COM	PAC	FAR
PRIMA astrometry data reduction library								
Requirement on data reduction library	Iss.0	Iss.1						
Performance verification matrix data reduction library		Iss.0	Iss.1					
Functional specifications of data reduction library		Iss.1						
Data analysis facility development and implementation plan		Iss.0	Iss.1					
Design of data reduction Library			Iss.1					
Prototype of DRL critical modules			v0.1					
Data reduction library source code					v0.1	v1.0	v1.x	v1.y
Demonstration				demo				
Simulated data					v0.1			
On-site implementation plan data reduction library		Iss.0			Iss0.1	Iss0.5	Iss1.0	Iss1.x
User manual data reduction library		Iss.0			Iss0.1	Iss0.5	Iss1.0	Iss1.x
Maintenance manual data reduction library		Iss.0			Iss0.1	Iss0.5	Iss1.0	Iss1.x
Functional description of calibration engine: algorithms applied							Iss1.0	Iss2.0
Principles at the base of data analysis facility							Iss1.0	Iss2.0

Documents with issue 0 refer to a draft. Software with version 0 refer to a beta release.

Table 3.3: Detailed overview of deliverables "PRIMA astrometry data reduction library".

	CDR	PDR	FDR	IRR	PAE	COM	PAC	FAR
General PAOS								
PRIMA OS - DRL interface control document	Iss.0	Iss.1	Iss.2				Iss.3	
PRIMA OPS - PRIMA OS interface control document	Iss.0	Iss.1	Iss.2				Iss.3	
AOS product assurance document	Iss.0	Iss.1	Iss.2				Iss.3	

Documents with issue 0 refer to a draft. Software with version 0 refer to a beta release.

Table 3.4: Detailed overview of deliverables "General PAOS".

3.2 PRIMA astrometric error budget

The error budget is the high-level tool to analyze the performance of PRIMA, to specify the requirements for its subcomponents and for data reduction tools, and to define the calibration and observing procedures. The error budget provides the metrics against which to verify the as-built performance of all components and procedures of the astrometric facility. ESO has specified the subsystems of PRIMA consistently with a $10\,\mu$as astrometric precision, but a formal error budget that includes all external (atmospheric, astrophysical, calibration) errors has not yet been constructed. This error budget forms the basis of the formulation of calibration and observation strategy, and for the specification of the PRIMA data reduction library and data analysis facility.

3.2.1 Description

Establishing the astrometric error budget for PRIMA consists of three separate steps:

1. Construction of a tree which breaks down the overall error into contributions from various sources.
2. (a) Allocation of admissible errors to subsystems and components starting from and consistent with the required precision (top-down).
   (b) Estimation of performance of subcomponents, external error sources, etc.; propagation of errors to the total precision (bottom-up).
3. Iteration of step 2, re-balancing the error allocations and improving the calibration procedures etc., until the top-down and bottom-up error budgets match.

Our present understanding of the error tree is sketched in Fig. 3.1, which gives a high-level overview of the various contributors to the total astrometric uncertainty.

3.2.2 Specific tasks

The next step will be translating the tree shown in Fig. 3.1 into an Excel spreadsheet (see Appendix A, i.e., attaching numerical multipliers based on an analysis of error propagation to each of the logical links in the tree. In some cases this is a rather involved task. For example, evaluating beam walk errors requires use of an optical model of the VLTI to compute the footprint of the metrology and starlight beams on each optical element, and knowledge of the surface errors of the optics. This completes step 1. in the list above; at this point we will have a spreadsheet with formulas in each cell, but no values yet.

Execution of step 2. requires further physical analysis of the effects contributing to the error budget, and gathering information about the predicted performance of all components. When this step is completed, we will have complete spreadsheets with values in all cells. Comparison of the top-down and bottom-up spreadsheets (step 3.) will then point towards potential problem areas. We will suggest further experiments and measurements to clarify open issues, mitigation strategies for risks identified, and improvements if the error budget cannot be balanced.

This study of the PRIMA error budget will need to be done in close collaboration with ESO. Hence extended visits of Consortium members to ESO will be necessary; the first such visit by Bob Tubbs and Rudolf Le Poole is currently taking place (from 23 February 2004 to 23 April 2004).

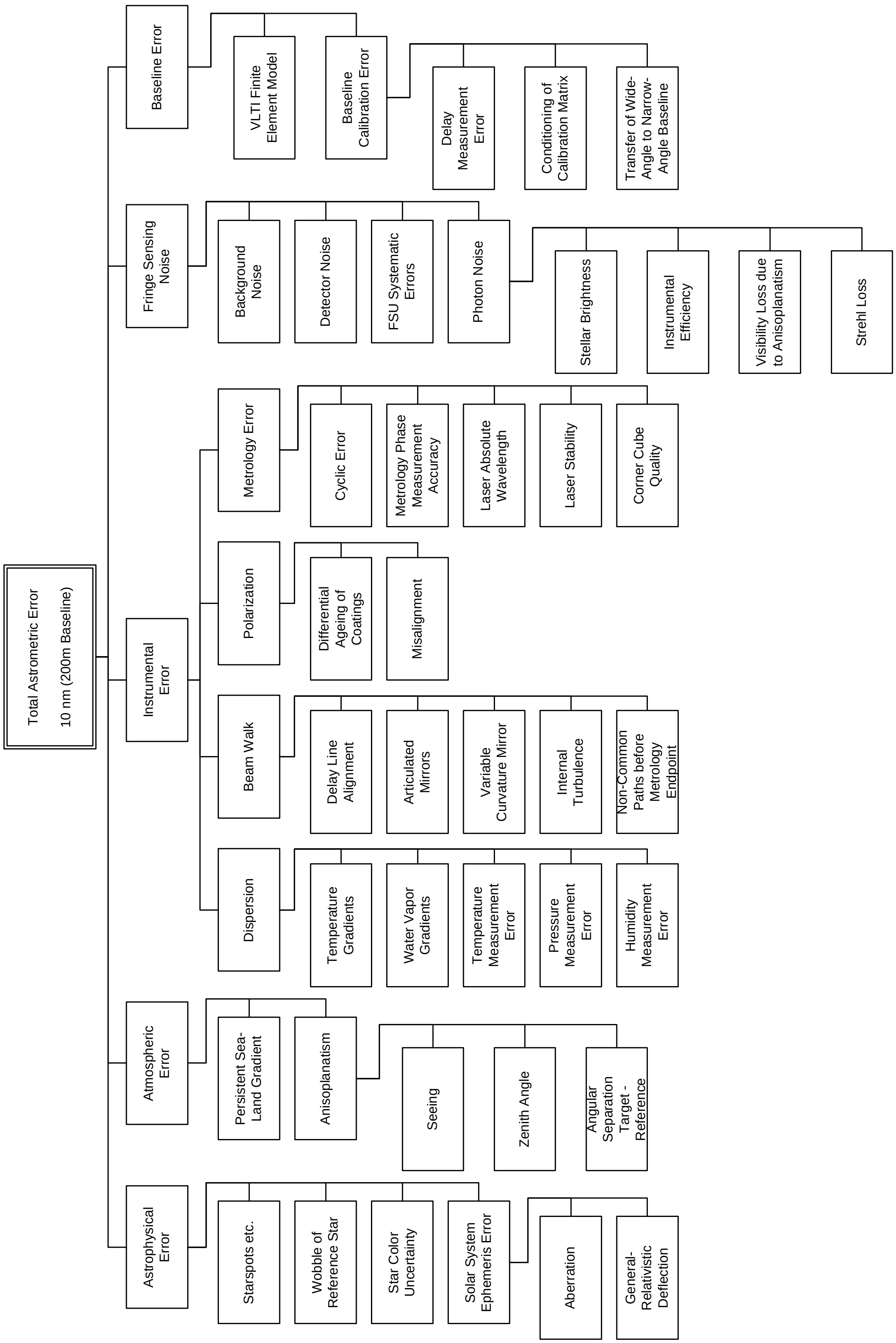

Figure 3.1: Sketch of the PRIMA error tree (only highest levels shown).

3.2.3 Excluded tasks

Tasks which are not included in this deliverables are:

- Algorithm development (this is included in the PRIMA data reduction design phase)

3.2.4 Dependencies

This deliverables requires input from:
PRIMA astrometry calibration and observation strategy

This deliverable is input to:
PRIMA astrometry calibration and observation stragegy
PRIMA astrometry data reduction library

3.2.5 CDR deliverables

- Preliminary report on the error tree (PRIMA astrometry error budget Issue 0), emphasizing identification of risks and areas in which additional experiments and measurements are needed.

3.2.6 PDR deliverables

- Document on the PRIMA astrometry error budget (document, Issue 1.0). This documents contains sections on:
  - Estimate of the error on the astrometric signal (in nanometer optical path length difference) per error term (bottom-up error budget).
  - Allowed tolerance of the error per error term (in nanometer optical path length difference) per error term (top-down error budget).
  - If needed, different scenarios to apply correction (e.g. hardware, software, calibration and observation strategy).
  - Identification of most efficient method to apply correction.
  - Document suggesting potential improvements to the VLTI infrastructure to enhance VLTI performance.
  - Preliminary Excel spreadsheet of error tree (included in the document);
  - Propose laboratory experiments, or experiments with the VLTI to asses the error terms.
  - Final Excel spreadsheet of error tree.

3.2.7 FDR deliverables

- Document on the PRIMA astrometry error budget (document, Issue 2.0). This document contains sections on:
  - In depth analysis for only those error terms which have been identified as being critical for the operations of PRIMA.

3.2.8 IRR deliverables

None

3.2.9 PAE deliverables

- Document on the PRIMA astrometry error budget (document, Issue 3.0). This document contains sections on:
  - Issue specified at previous phases.

3.2.10 PAC deliverables

None

3.2.11 FAR deliverables

- Document on the PRIMA astrometry error budget (document, Issue 4.0). This document contains sections on:
  - Analysis, evaluation and identification of the long trend effects on the real GTO data

3.3 PRIMA astrometry calibration and observation strategy

3.3.1 Description

As explained in Sect. 2.2, PRIMA will perform triple-differential measurements, i.e., differences of large numbers have to be taken in several steps of the data reduction. Through this process, we will be able to detect 5 nm effects in 200 m delay data. This implies immediately that any losses of zero points, or unrecognized minute changes of scale, will lead to catastrophic failure. Proper calibration and planning of the observations is therefore as important as ensuring flawless performance of the hard- and software.

Therefore, a detailed calibration and observation strategy has to be developed, which includes selection criteria for proper selection of astrometric calibrators, phase-referencing sources, and a special list of instrumental calibrators. This task is intimately linked to establishing a PRIMA astrometry error budget.

As we are interested only in the errors *after applying all the necessary calibrations, and performing the appropriate differencing.* In addition, the calibration and observation strategy is needed as an input to specifying the data reduction library and data analysis facility, as these will have to implement the calibration procedures.

Calibration of elementary observations

The calibration plan for PRIMA foresees executing a calibration procedure at regular intervals, in which the light from the primary star is sent down both the target and reference path of the dual-star interferometer. Details of this procedure have to be specified for the observing templates. Other potential calibrations (e.g., detector background measurements) have to be specified and incorporated.

Auxiliary data

The primary observable of differential astrometry is derived from the outputs of the end-to-end metrology and of the fringe sensing units (see Eqn. 2.1). In practice, however, corrections have to be applied that are derived from telescope parameters (e.g., zenith angle, delay line positions, ...) or from the outputs of auxiliary sensors (e.g., ambient pressure, temperature and humidity in the delay line tunnel, ...). The calibration and observation strategy will specify which inputs are needed for the calibration and data reduction, and how the corresponding calibrations will be applied to the primary data.

Scheduling of observations

The scheduling of observations could potentially have a strong influence on the ultimate precision of PRIMA, as some types of systematic errors can be eliminated by judicious scheduling. For example, one might be concerned that the proximity of Cerro Paranal to the Pacific coast could give rise to a persistent East-West gradient of the atmospheric pressure and / or humidity profile, and thus to a "prismatic wedge" above the observatory. The influence of such a wedge could effectively be eliminated by always observing a given target at the same hour angle. The advantages of such an observing strategy have to be weighed against the loss of flexibility; absolute-time-driven (in contrast to the usual integration time-driven) observing preparation tools and observing templates would be needed.

Astrometric reference star selection

The success of an astrometric observation with PRIMA depends critically on the proper choice of the reference star, which in the astrometric mode will usually be fainter than the science target and in practice be the secondary star. The reference star should a distant background star close (in projection on the sky) to the science target ($\lesssim 30'' \ldots 1'$) to limit the effects of anisoplanatism, relatively bright ($K \lesssim 16 \ldots 17$) to avoid excessive fringe sensing noise, and astrometrically stable over the duration of the observing program. As part of the calibration and observation strategy, we will evaluate the trade-offs inherent in the choice of suitable reference stars, and produce a guide for other potential users of PRIMA, enabling them to apply reasonable selection criteria to reference stars for their observing projects.

Baseline calibration

The baseline vector has to be known with a precision of $\sim 50\,\mu$m (see Sect. 2.2). It is foreseen that the baseline will be determined from observations of stars with known positions, in the same way as radio interferometers obtain their baseline solutions. This procedure works best if the stars from which the solution is obtained cover large ranges in zenith angle and azimuth; a careful trade-off between the time required for the baseline solution and the conditioning of the baseline calibration matrix is therefore required. An optimized algorithms that provides the best trade-off between the required calibration time and accuracy of the baseline solution will be given. Another factor entering this trade-off will be the relative stability and predictability of the AT mechanical structures, which determines the intervals at which the baseline solution has to be repeated; a finite-element model of the ATs will likely have to be incorporated in the baseline solution software.

The Consortium provides the algorithm for baseline calibration (in the data reduction library) and a list of baseline calibrators (in this deliverable). For each calibrator details are listed among which their quality to act as calibrator.

Instrumental calibrators

In some instances it may be preferable to calibrate instrumental effects not from first principles, but by empirical parameterizations – examples may be color- or spectral type-dependent biases. For such empirical calibrations, lists of well-characterized calibrators covering the relevant parameter space are needed.

Verification targets

PRIMA will conduct very challenging observations in the quest for observing planets with previously unattainable precision. It is thus necessary to verify the performance of PRIMA with test targets that exercise the capabilities of PRIMA, with predictable results. For example, bright visual binaries with separations in the range $10'' \ldots 20''$ will give high-signal-to-noise fringes in both FSUs, allowing verification of the atmospheric model, high-frequency response of the fringe servos etc. In a similar vein, observations of spectroscopic binaries with known orbits enable verification of the observing and data reduction procedures with signatures orders of magnitude above the required accuracy. Test sequences have to be defined, and suitable target lists need to be compiled from binary catalogs.

Calibration and observation strategy

The PRIMA astrometry calibration and observation strategy is a document that specifies alternative operation and calibration modes, and for each the implications on the data reduction, efficiency of observations, and other related issues. The strategy is written by scientists and engineers who are very familiar with the overall PRIMA astrometry error budget, the data reduction requirements and the scientific observations planned with PRIMA. Therefore, the strategy presents a matrix that demonstrates the implications for each mode for a number of relevant parameters (observing efficiency, accuracy, overhead, easy of use etc.).

This document will discuss a number of alternative calibration strategies and a comparison on how this will affect the operations of PRIMA. A minimum requirements is that this document will discuss five techniques to calibrate PRIMA:

1. Calibration using visual binaries by which the primary and secondary component of the binary system will be detected by FSU A and B respectively;
2. Calibration using a well-defined set of calibrator pairs (a so called calibration grid). These pairs could party overlap with targets from the GTO program;
3. Calibration using technical procedures e.g. splitting the light of a single two by the Star Separator;
4. Self calibration of the science stars by adequate sampling of the astrometric parameters (e.g. tracking a star for many hours);
5. Any combination of the above mentioned.

This document discusses for each of the alternative calibration modes (and possible additional ones):

1. How large the set of calibrators should be (if applicable);
2. How often the calibration should be repeated (e.g. nightly, weekly, only if baseline changes);
3. Estimate on how much observing time needs to be allocated for calibration;
4. Requirements on the VLTI infrastructure for this calibration mode;
5. Requirements on the PRIMA software for this calibration mode:
   (a) PRIMA astrometry Observation Preparation Tools;
   (b) PRIMA astrometry Data Reduction;
   (c) PRIMA astrometry OS;
   (d) PRIMA astrometry Data Flow.
6. The expected performance of this calibration technique.

This document will discuss a number of alternative operations strategies and a comparison on how this will affect the operations of PRIMA. A minimum requirements is that this document will discuss the following operations strategies

1. An optimal observation strategy taking into account only the needs for PRIMA astrometry;
2. An optimal observation strategy taking into account other modes of operations of PRIMA (e.g. imaging, and faint source science);
3. An optimal observation strategy taking into account other modes of operations of VLTI (e.g. AMBER, MIDI, GENIE, FINITO).

This document discuss for each of the alternative operations modes (and possible additional ones):

1. Requirements on the VLTI infrastructure (e.g. frequency of change of baseline, operating multiple VLTI instruments during one night, change operations from one wavelength to the other);
2. Scheduling observations in visitor mode versus service mode;
3. Overhead on effective observation time;
4. Requirements on the VLTI infrastructure for this operation mode;
5. Requirements on the PRIMA software for this operation mode:
   (a) PRIMA astrometry Observation Preparation Tools;
   (b) PRIMA astrometry Data Reduction;
   (c) PRIMA astrometry OS;
   (d) PRIMA astrometry Data Flow.
6. The expected performance of this operation mode.

In addition to this, the calibration and observation strategy will discuss a number of different science cases. For each of these cases, the document will discuss:

1. Brief overview of the most important science case (e.g. exo-solar planets, short term binaries with a period of days or less, Galactic Center);
2. The implications on the frequency of observations, accuracy on the measurements, for these cases;
3. Which calibration and which observation strategy would be most appropriate for these science case;
4. The expected performance of PRIMA astrometry for this science case. Where the expected performance will be expressed in reaching the science objective (e.g. orbital parameters for an exo-solar planet, mass of central black-hole of Galactic Center), and not necessary in the astrometric data in micro-arcseconds.

A calibration and observation strategy does not decide on which strategy is most suited mode to operate PRIMA.

The calibration and observation strategy document provides input to the calibration and observation plan.

Calibration and observation plan

Based on the document "calibration and observation strategy", the PRIMA instrument scientist will make a trade-off analysis of the alternative operations and calibration strategies, takes into account the scientific return and operations constrains at Paranal, and proposes an calibration and observation plan.

The calibration and observation plan is not a formal deliverable from the Consortium, but falls under the responsibility of the ESO PRIMA instrument scientist. The Consortium will provide assistance to the PRIMA instrument scientist whenever requested.

The calibration and observation plan will be a detailed description on how a observing night with PRIMA astrometry will be. It discusses among others:

1. How to start-up the PRIMA system (e.g. will there first be a baseline calibration?);
2. The order in which calibration procedures (zero OPD, baseline, etc.) have to be performed and what procedures are used;
3. How are the science targets for the night selected (e.g., weather conditions, hour angle range, priority and time constraints for individual targets, etc);
4. What is the procedure before an exposure can start (e.g. first pointing the ATs, fine acquisition of the source on both telescopes, fringe search for both sources, opd stabilization, exposure with on-line quality control);
5. Requirements on the VLTI infrastructure for this operation and calibration mode (e.g. access to Delay Line Tunnel, access to metrology information) ;
6. Requirements on the PRIMA software for this operation and calibration mode:
   (a) PRIMA astrometry observation preparation tools;
   (b) PRIMA astrometry data reduction;
   (c) PRIMA astrometry OS;
   (d) PRIMA astrometry data flow;
   (e) PRIMA astrometry templates.
7. Expected performance of the calibration and observation plan;
8. The calibration and observation plan will not contain any data reduction algorithms, but is rather a detailed description of an observing night with PRIMA.

The calibration and observation plan document provides input to the requirements on the PRIMA astrometry templates.

PRIMA astrometry templates

The PRIMA astrometry templates is the top-level software package that control PRIMA in astrometry mode. It sends commands to the PRIMA subsystems and the overall VLTI control system (ISS). The functional specifications of the templates will be based on the calibration and observation plan.

3.3.2 Specific tasks

- Establish requirements on special calibrators and verification targets (e.g. binaries, magnitude, spectral type, motion);
- Compile a list of calibrators;
- Compile a list of verification targets;
- Provide required information on special calibrators; (e.g. K-band spectrum and magnitude, other relevant properties);
- Provide required information on verification targets; (e.g. K-band spectrum and magnitude, other relevant properties);
- Write user guide with reference source selection criteria;
- Write functional specifications of PRIMA astrometric templates (as part of the science support);
- Define calibration and observation strategy (what, frequency, how ...);
- Write calibration and observation strategy;
- Iterate between calibration strategy and error budget.
- Support ESO in developing an calibration and observation plan (as part of the science support);

3.3.3 Excluded tasks

Tasks excluded in this deliverable are:

- Selection of actual reference stars for specific observing programs (this has to be done as part of preparation by individual observers);
- Design of the PRIMA astrometry templates;
- Coding of the PRIMA astrometry templates.

3.3.4 Dependencies

This deliverables requires input from:
PRIMA astrometry error budget

This deliverable is input to:
PRIMA astrometry error budget
PRIMA astrometry data reduction library

3.3.5 CDR deliverables

- Calibration and observation strategy (document, Issue 0);
- Calibration and observation plan (document, Issue 0);

3.3.6 PDR deliverables

- Calibration and observation strategy (document, Issue 0.1);
- Calibration and observation plan (document, Issue 0.1);
- Requirements on PRIMA astrometry templates (document, Issue 1).
- Requirements on PRIMA astrometry calibrators (document, Issue 1).
- Requirements on PRIMA astrometry reference sources (document, Issue 1).

3.3.7 FDR deliverables

- Calibration and observation strategy (document, Issue 1);
- Calibrator source requirements (document, Issue 2).
- Reference source requirements (document, Issue 2).
- Design of the PRIMA templates (document, Issue 1) (ESO responsibility).

3.3.8 IRR deliverables

None

3.3.9 PAE deliverables

- Calibration and observation strategy (document, Issue 2);
- List of calibrators (document), e.g list of special calibrators, K-band spectrum and magnitude of calibrators, and their properties;
- Calibration and observation plan (document, Issue 1) (ESO responsibility);
- Library of PRIMA astrometry templates (software, version 1) (ESO responsibility).

3.3.10 PAC deliverables

None

3.3.11 FAR deliverables

None

3.4 Observation preparation tools

3.4.1 Description

The scientific potential of the state of the art VLTI/PRIMA astrometry machine, in the field of extra-solar planet search and characterization has been demonstrated provided that the 10 microarcsecond accuracy is achieved. Reaching such an accuracy is both a technical and a signal processing challenge which is now being addressed by the consortium. Nevertheless, one should keep in mind that the scientific outputs of the VLTI/PRIMA astrometric mode could be dramatically increased if a careful observation scheduling is implemented. Indeed, like all interferometric measurements, individual astrometric measurements are time consuming (at least 30min/measurement). For instance, the basic determination of the parallactic motion will take at least 15 measurements spread at optimal phases over 1.5 years. 15 extra measurements should be added to derive the astrometric orbit making a total of 30 measurements per star. These numbers translate into 15 hours observation per star spread over 3 years provided that they are carried out at optimal phases.

Another difficulty comes from the survey nature of astrometric observations. We need to optimize the observation for a large sample of star, which cannot be done manually. For example, if the star sample is composed of 100 stars, it translates into 1500 measurements that should be correctly scheduled over several years. Inefficient scheduling (bad set of VLTI configuration and observing date) would prevent accurate parallax determination in 2-year-period and thus it would prevent planet search or characterization over a time-span of 3 years (Fig.3.2).

Observation preparation software description

The observation preparation software (OPS) will help the observer to schedule observation of a given (or several) target(s) over several years. As an input it will accept a target list, composed of scientific target, reference star(s), proper motions, parallaxes, magnitudes and precise coordinates. The OPS will access a second database consisting of all VLTI baseline configuration that will allow to compute for different set of baselines and dates, projected differential delays. From the projected delays and the magnitude of the targets, an integration time will be computed. The OPS will then propose to the observer a set of baseline configuration, observing dates and integration time to choose from. Once the final planning is chosen, the OPS should be able to create Observing Blocks (OB's).

Observation preparation software modules and interfaces

The observation preparation software (OPS) consists of a set of ANSI-C/Java libraries that will be interfaced to the Web Graphical Interface by ESO. OPS should be accessible to the astronomical community via Web pages like the ESO Visibility Calculator (VisCalc) and all ESO instruments Exposure Time Calculator (ETC). The OPS should also be accessible locally at Paranal Observatory (no internet dependency). Fig.3.3 is a schematic representation of the different Observation Preparation Software modules that are described in more details below

Target database preliminary format

It should be a tabulated separated ASCII table in the starbase format with the following entries. These entries are preliminary.

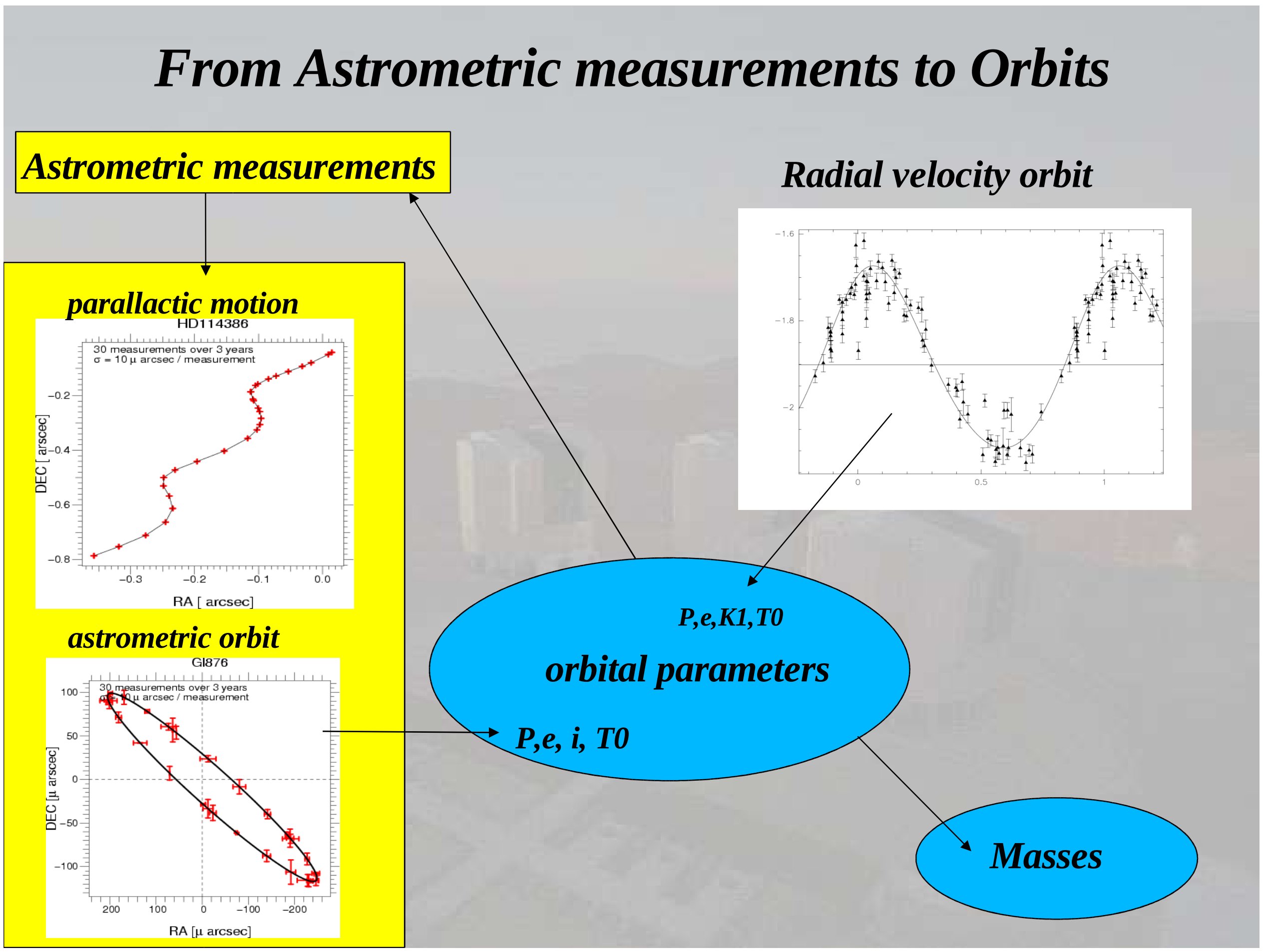

Figure 3.2: This figure illustrates the different steps required to search and characterize extrasolar planets. It shows the parallactic motion of HD 114388 only (no reference star) over a 3-year-period. The red crosses correspond to two orthogonal astrometric measurements with 10 μarcseconds accuracy. For example, if no measurements are scheduled at the oscillation extrema, the derived proper motion and parallax will be false and no planetary signal could be retrieved out of the observations.

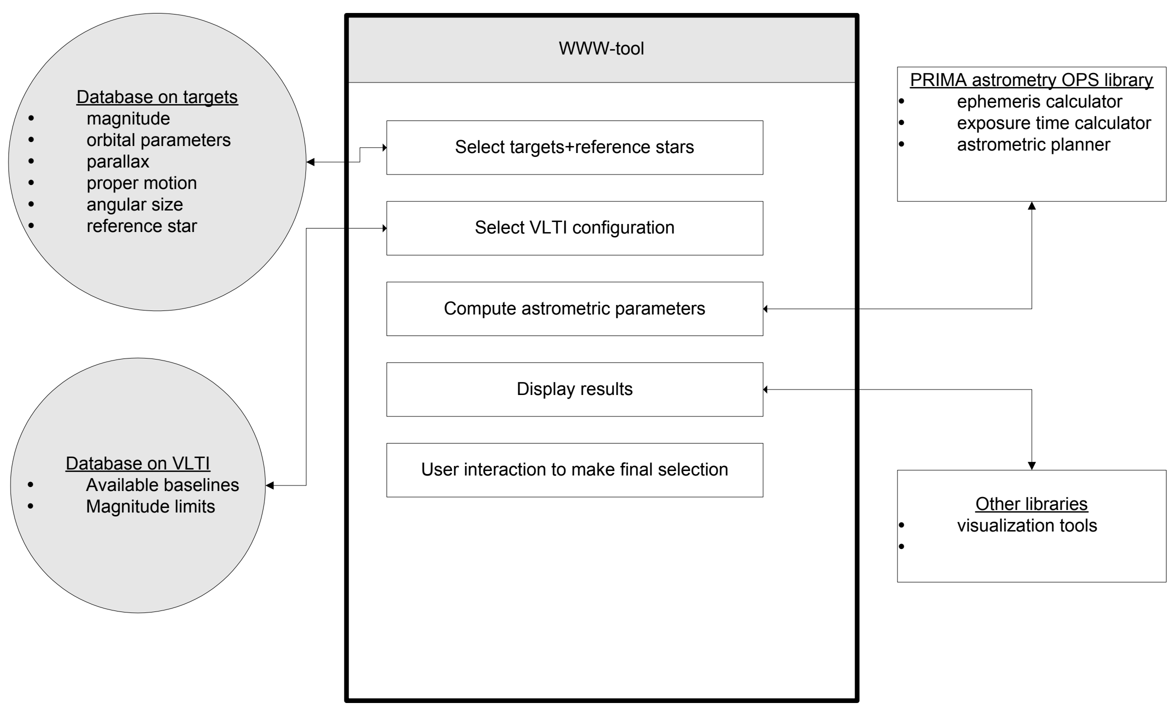

Figure 3.3: This figure illustrates the main modules of the observation preparation software and how they interact with each other.

- Target identifier (reference star, scientific target star);
- Identificator (HD2345, HIP2345, BD3456);
- Reference star identifier : 1, 2, 3 (there could be several reference stars);
- Rho reference star-scientific separation;
- DX reference star-scientific target east-west separation;
- DY reference star-scientific target north-south separation;
- RA;
- DEC;
- Epoch;
- Spectral Type;
- Proper motion alpha;
- Proper motion delta;
- Parallax;
- V mag;
- K mag;
- Activity log(H');
- Metallicity (Fe/H);
- Rotation velocity (v sini);
- Orbital motion flag (0 no data / 1 known planet):
  - Period;
  - T0;
  - K1;
  - e;
  - a sini;
  - omega;
  - Omega.

Ephemerids calculator

The goal of the ephemerids calculator is deliver accurate ephemerids given a projected baseline, parallactic motion and orbital elements in order to efficiently schedule the observations. No fitting procedures will be delivered.

- Projected baseline calculator:
  - Input:
    - VLTI configuration (Baseline, dome vignetting, delay line stroke limitation);
    - Date, time;
    - RA, DEC of the target and reference star.
  - Output:
    - projected Baseline.
  - Delivered:
    - ANSI-C routines.
- Astrometric motion calculator:
  - Input:
    - RA, DEC, parallaxes, proper motion of the target and reference star;
    - Date, time.
  - Output:
    - Astrometric motion (in coordinate system).
  - Delivered:
    - ANSI-C routines.
- Projected delay calculator:
  - Input:
    - Astrometric motion;
    - Projected Baseline.
  - Output:
    - Astrometric delay observed for a given projected baseline.
  - Delivered:
    - ANSI-C routines.

Exposure time calculator

Given a required astrometric accuracy provided by the astronomer (such as 10 or 30 microarcsec), a VLTI configuration and the angular separation between the scientific target and the reference star, the ETC should return the integration time to reach such an accuracy. If this time is too large (ie. larger than 30 minutes) or if the reference star is too far away, the software will deliver a warning and propose to work at lower accuracy. This ETC should also take into account the VLTI-PRIMA-DDL overheads which are foreseen to be considerably larger than the total integration times in order to estimate the time spent on a given target.

- Input:
  - Target and reference star magnitude;
  - Target-reference star separation;
  - Delay accuracy.
- Output:
  - Integration time;
  - Warnings if integration time is too long or if accuracy is impossible to reach.
- Delivered:
  - ANSI-C routines.

Observation preparation software delivery

We will deliver a complete documentation to ESO describing the formula we used and the algorithm. We will also deliver a prototype of the software to ESO which will be written in either IDL or MATLAB. The final product will consist of a set of ansi-C/JAVA routines that will be interfaced with User Friendly Graphical User Interface by ESO. It should be accessible both from the web (like VisCalc, ETCs') and locally at Paranal (like HARPS STS)

3.4.2 Specific tasks

Specific task are:

- Functional specifications;
- Design prototypes;
- Deliver Ansi C codes;
- Provide documentation.

3.4.3 Excluded tasks

- Web-interface;
- Software conform ESO standards.

3.4.4 Dependencies

This deliverables requires input from:
PRIMA calibration and observation strategy

This deliverable is input to:
PRIMA astrometry data reduction library

3.4.5 CDR deliverables

- Requirement on observation preparation tools (document, Issue 0).

3.4.6 PDR deliverables

- Requirements on observation preparation tools (document, Issue 1);
- Performance verification matrix (document, Issue 0);
- Functional specifications of observation preparation tools (document, Issue 1).

3.4.7 FDR deliverables

- Performance verification matrix (document, Issue 1);
- Design of observation preparation tools (document, Issue 1);
- Prototypes of critical modules (software, version 0.1).

3.4.8 IRR deliverables

An IRR demonstration (with the consortium) will demonstrate that the tools will be compliant with the requirements.

3.4.9 PAE deliverables

- Library of observation preparation tools (software, version 1.0);
- On-site implementation plan of observation preparation tools (document, Issue 1.0);
- User manual of observation preparation tools (document, Issue 1.0);
- Maintenance manual of observation preparation tools (document, Issue 1.0).

3.4.10 PAC deliverables

- Library of observation preparation tools (software, version 1.x);
- On-site implementation plan of observation preparation tools (document, Issue 1.x);
- User manual of observation preparation tools (document, Issue 1.x);
- Maintenance manual of observation preparation tools (document, Issue 1.x).

3.4.11 FAR deliverables

None

3.5 Data reduction library

3.5.1 Description

This section describes those software components which will allow ESO users, including the current proposers, to calibrate their astrometric observations to the desired 10 μas accuracy. There is only one actual deliverable, the library, but this section also describes two intermediate steps, the requirements analysis and the design analysis of the library, in order to give ESO more insight into the phasing of the work. The library contains the modules listed in Table 3.5, and for each module we give a brief description of its functionality. All these modules will be a deliverable to ESO and will comply with the ESO standard using in particular the ESO Common Pipeline Library (CPL). As there are no formal ESO standards on the interactive environment, Table 3.5 mentions explicitly the software language which has been proposed as the standard by the Consortium.

Table 3.5: Overview of software modules of the PRIMA astrometry data reduction library.

Module	Acronym	Standard	Pipeline Module	IDAF Module
Scientific Algorithms	SA	ANSI-C/CPL	Y	Y
Numerical Recipes	NR	ANSI-C/CPL	Y	Y
Calibration Engine	CE	ANSI-C/CPL	Y	Y
Quality Control Recipes	QC	ANSI-C/CPL	partly	Y
Graphical User Interfaces	GUI	JAVA	N	Y
Trend Analysis Tools	TA	JAVA	N	Y
Visualization Tools	VT	JAVA	N	Y
Data Base	DB	SQL	N	Y
Server	SE	JAVA	N	Y
Simulated data	SD	FITS	Y	Y

Scientific Algorithms All the algorithms required for performing the astrometry data reduction.

Numerical Algorithms A collection of general numerical algorithms for common tasks, such as fourier transforms, integration, fitting, etc.

Calibration Engine Computes for a given set of parameters the correction to the delay based on known systematic errors. This engine is initialized from the IDAF with the latest results from the trend analysis, but can operate stand-alone within the pipeline.

Quality Control Test procedures and code for verifying the scientific and technical performance of PRIMA astrometry.

Graphical User Interfaces The top-level user interface to the whole IDAF, including the visualization tools. Can be enhanced with plugins as new analysis tools are to be added.

Trend Analysis Tools Tools for analyzing the night-to-night data as function of a series of parameters for which possible systematic dependencies are to be expected.

Visualization Tools Provides standard 2D diagrams (line, contour, grayscaling, scatter, etc.) and integration of those diagrams in interactive GUIs.

Data Base Contains all the information about the organization of the raw data, the dependencies between different steps and the results of the trend analysis.

Server Provides multi-user server-client access to the IDAF, which is supposed to run on a single computer. The GUI will access this server over the internet.

Simulated Data A realistic simulation of a multi year set of observations, which is to be used to test both the pipeline and IDAF. This data-set will be used for an integral test of both the technical and scientific performance of whole system (pipeline and IDAF).

3.5.2 Introduction

High accuracy astrometry data cannot be calibrated on the basis of a few calibration measurements made close in time to the scientific observations. All such projects have shown that removal of instrumental effects requires accumulation of calibration information over long periods (years), human analysis of the trends in this information, formulation of algorithms to remove these instrumental effects, coding of these algorithms, and application of the (new) calibrations to data. These steps must be repeated several times as more information becomes available.

Traditionally this has been a batch processing procedure: as a new problem or set of parameters is identified, all existing data is reprocessed.

The ESO user's environment for PRIMA may require modification of this approach if individual users want re-calibration of small subsets of data. Note, however that the batch processing approach has been successfully applied in multi-user projects such as ISO.

For each phase the same set of library routines will be accessed. This concept of phase data reduction is visualized in Fig. 3.4, and is based on experience the Consortium has gained in the development of the data reduction packages for VLTI/MIDI, HARPS, and Sauron (WHT on La Palma).

The calibration system will operate in the initial period as follows:

1. Immediately after data acquisition an on-line pipeline is run. This compresses the data streams (by factors 10-100) and applies a crude as-of-date calibration. Both raw and compressed data are stored in the ESO archive. Most off-line re-calibration steps need only deal with the compressed data (intermediate data product);

2. Copies of all raw data will be assembled by the Consortium. Compressed Engineering data and some extracted astronomical measurements are stored in the IDAF database.

3. The Consortium will analyze these measurements, using the **Interactive Data Analysis Facility** (IDAF) looks for systematic errors in the results (trend analysis), correlates these errors with engineering data, and formulates corrective algorithms. These algorithms are coded and installed in the IDAF and in the ESO pipeline;

4. An updated calibration engine, and scientific and numerical algorithms for the pipeline will be released by the consortium on a regular basis. Between PAE and FAR the goal is to release updates every 6 months. However the implementation of these strict dates will need to be negotiated with ESO depending on the improved performance of each update, in relation to the required efforts to update the pipeline and reprocess all available data;

5. Updates of the calibration engine, trend analysis and visualization tools, data-base etc. in the IDAF will be made continuously, as the IDAF will also be used as developing environment;

6. When the dependence of corrections on engineering and astronomical data is established a **Parameter Extraction Algorithm** is also formulated. This describes searching the database

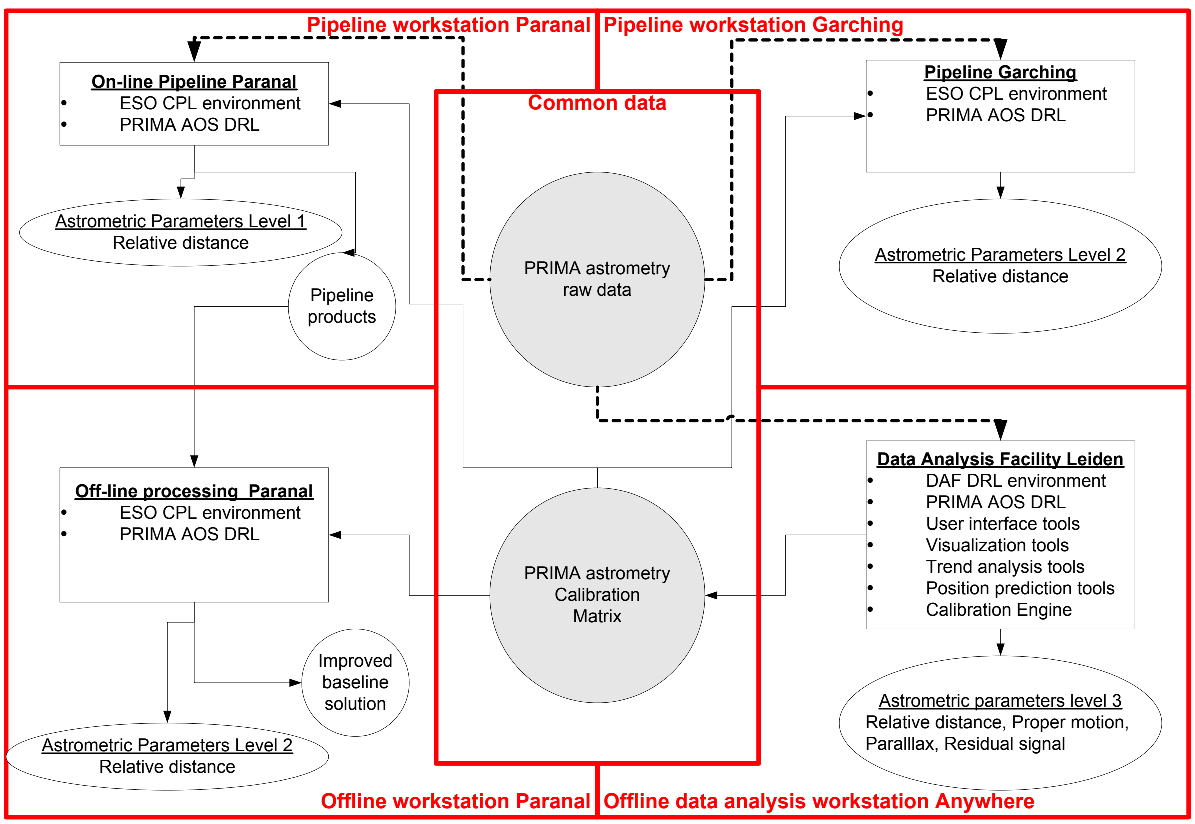

Figure 3.4: This flow diagram shows on the left the software which runs at Paranal on the raw data. On the right it shows the main components of the software that runs in Europe on the raw data. Some files are in common (the PRIMA AOS DRL), the Calibration Engine and Matrix, and of course the raw data.

for the appropriate data, and calculating the inputs to the pipeline procedures. This algorithm may be complicated, involving interpolation and cross-correlation of various data streams, but it is at this phase non-interactive. This process can be described as a **Parameter Generation Engine**, incorporating database and extraction algorithms;

7. At this point any observation can be calibrated, insofar as the significant problems have been analyzed in steps (3.) and (4.). These steps will create repeated updates to the system throughout the GTO period.

Excluded tasks

1. Helpdesk services for the rest of the community. The Consortium only delivers calibrated data, or the software infrastructure to calibrate data (e.g. calibration engine and matrix).

In addition to the final deliverables, the consortium has defined two milestones in order to review progress and adjust goals (requirements and design).

3.5.3 PRIMA astrometry data reduction requirements

Description

This milestone deals with the requirements on the astrometric data reduction library. The primary deliverable will be a document (the **Data Reduction Library Specifications** document, in the following DRLS document), to be delivered at PDR, specifying the requirements on the astrometric data reduction. These requirements fall in several broad categories:

Direct astrometric requirements

These are derived from the basic requirement to deliver calibrated data to the specified accuracy. In detail, they will be coupled to output of the error budget and calibration and observation strategy deliverables. For each error contribution term identified there, the DRLS document shall contain a list of calibration parameters as well as additional input parameters/measurements that are needed to correct for the particular error term. Furthermore, it should specify a strategy how to correct for the effect so that the resulting astrometric error is reduced or completely removed. In case the removal of the particular error term requires additional observations or an elaborate calibration strategy to be eliminated, the DRLS document should also specify these observations and strategies.

In addition to the error terms to be discussed in the Error Budget document, there will very likely be further error sources/effects that can only be discovered in the actual data taken with PRIMA. The trend analysis, running on a large data set, should identify such potential further error sources. Once such an additional error term is identified that had not been anticipated before, the error budget document as well as the DRLS document will have to be updated, and appropriate actions have to be taken to correct for these terms. A requirement on the data reduction library is thus that is should be built in such a way that additional error terms can easily be added later on. For an example of the PRIMA Astrometry data flow see Fig. 3.4. In other words, the data reduction library should have the capabilities for continuous updates.

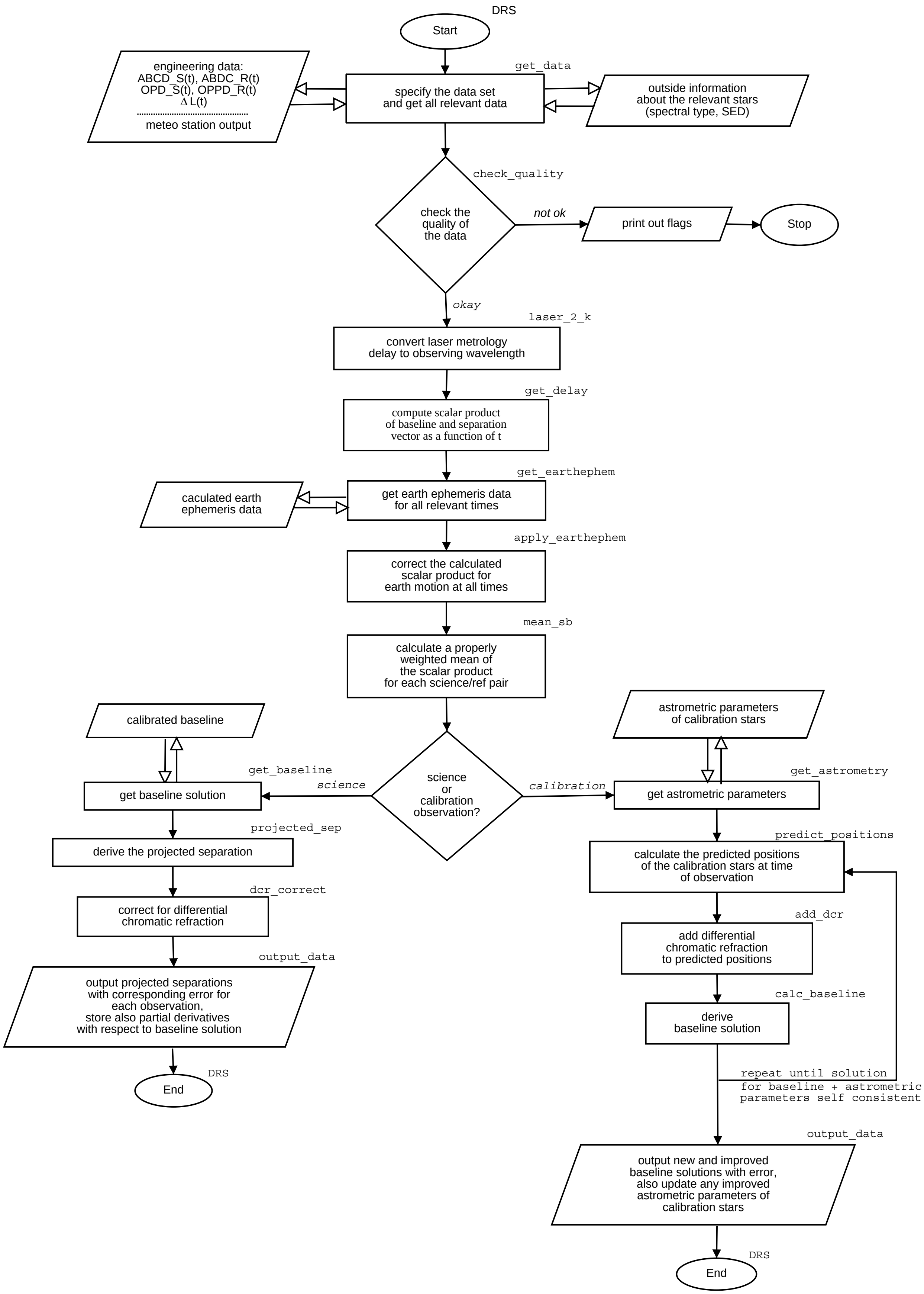

Figure 3.5: Flow chart for DRS scientific recipes.

Global reduction requirements

Global requirements on the data reduction library include the ability to easily revert to earlier versions ('accounting trail') as well as suitable user interfaces that provide plotting and simple analysis tools of the data. Furthermore, the data reduction library has to run on suitably compressed data. The compression algorithm and format has to be defined in such a way that it allows all subsequent data reduction without having to revert to the original data. Detailed requirements on the data compression will be provided in the DRLS document, constrained again by the error budget. Also overall throughput and storage requirements will be specified here.

Conventions, notations and standards

In order to facilitate the development of the error budget and DRLS documents it is highly desirable that an additional document is produced at the very early stages of the project (soon after kickoff) that deals with conventions, notations and standards. In this document, which is not a formal deliverable to ESO, all parameters that enter the error budget or the astrometric data reduction have to be clearly and unambiguously defined. The same holds true for all coordinate systems that are employed. In this section standards for documentation will also be defined.

Data Interfaces

Data interfaces with external data streams, primarily ESO engineering systems, the ESO Pipeline system, and the ESO archive system, will be identified, and standards for the data formats should be defined. This will also enable the generation of a set of simulated data that adhere to the specified format for test purposes of the library.

User Interfaces

Requirements for interfaces with interactive users of the system will be specified.

Performance requirements

During the early stage of the project, performance requirements on the PRIMA Astrometry data flow will be defined. An example of such a performance verification matrix is presented in Table 3.6.

Calibration engine and calibration matrix

The full data-set of PRIMA Astrometry data available to the Consortium will be organized through a database system. The Interactive Data Analysis Facility (IDAF) will use the data-base and the archive to allow interactive search for trends. Once a trend has been identified, a corrective algorithm will be hard-coded in the calibration engine. The calibration engine generates a calibration matrix for each observation (observation block). The calibration matrix contains the error term which the pipeline needs to correct the raw data to science grade astrometric observables.

The calibration engine can be improved by adding additional algorithms based on insights obtained using the IDAF, or any other method or technique.

Data reduction phase	Target astrometric accuracy	Maximum clock time needed to reprocess
Pipeline solution	50 micro-arcseconds	< 5 minutes (for 1 OB)
Nightly solution	25	< 8 hours (for full night of data)
Global solution	10	< 5 days (for full data-set)

note, these numbers are not factual, but only serve as an explanation

Table 3.6: Example on performance specification for the different phases of PRIMA astrometric data reduction.

3.5.4 PRIMA astrometry data reduction design

Description

For the second milestone, based on the functional specifications, a detailed design of the data reduction software system will be made. This will include both the design of the general system architecture and the applications to implement specific calibrations. It is proposed to write the design in the Unified Model Language (UML), which is the most widely used object oriented design language. A CASE tool will be used to do round trip software engineering between the UML diagrams and the code. However, this design method is only applicable to the IDAF, since the ESO pipeline will be written in ANSI C. This language does not support OO design and development and the non-interactive nature of the pipeline can be described well with a procedural approach. In any case an iterative design/development process will be chosen, since it is not possible to make a final design for the whole system before starting the coding. Changes of understanding will inevitably lead to changes in the design.

The Data Analysis Facility (DAF) will require an interface which allows the astronomers to have control on all raw and intermediate data leading to the final overall calibration required for the scientific data product. The calibration process itself will include the analysis of systematic trends which are not always known in advance, but the information in the system should remain consistent and well defined at all times. Therefore, the system requires both the flexibility to cope with new insights and the robustness required for processing a large data-set consistently. This can best be reached by an underlying relational database, which contains all information about what has been done with the raw data in order to obtain the final calibration. Upon this database a layer of middle-ware should be created which defines the procedures on how to interact between the database, the scientific algorithms and the user interface. This middle-ware should make sure that all the data in the data-base remains consistent by satisfying all dependencies in case of a change at a certain level in the analysis. The middle-ware will have a common architecture in which the scientific analysis steps can be inserted as plugins and the recipe defined in a configuration file. Also, the user interface will get plugins to define different visualizations of the data.

Specific tasks

1. Analyze the functional specifications and determine where and how much flexibility is required to allow for improvements or changes in the data analysis methods;

2. Describe all the reduction algorithms and their dependencies as detailed as possible at this stage;

3. Analyze the complete information flow and determine how the data will be handled and stored.

Define for the IDAF a database model and the formats for accompanying data and configuration files. For the pipeline the file formats for the input information must be defined, as well as the format for the data product file. The input information from the pipeline comes from both the raw data and the IDAF calibration product;

4. Collect a library of appropriate numerical algorithms;
5. Select the software for doing the design and development. This includes a UML design program, a CASE tool and an IDE. The IDE must be suitable for all languages used in the projects, although the CASE tool will probably not be used for the ANSI C code. A decision on open source vs commercial tools shall be based on a cost/benefit analysis;
6. Collect the appropriate tools to meet the requirements on the user interface, visualization and data handling of the IDAF. These tools must be available as re-usable object oriented code in order to be able to easily integrate them in the design;
7. Do a procedural design of the pipeline code, which is to be coded in ANSI C. This design will contain all the functions for the reduction recipe, the C structures for information exchange, and the design of the CPL based infrastructure. The algorithms must be clearly distinguished from any pipeline data handling infrastructure in order to reuse them as easily as possible inside the IDAF;
8. Define an API between the algorithms and the IDAF;
9. Do a full UML design of the IDAF in which the algorithm functions are integrated as methods in the class diagrams. The UML design should be good enough to generate template code with a CASE tool and includes the data handling, user interaction and visualization;
10. Prototype some critical parts of the system to test the approach of the first design;
11. Develop the code and improve the design iteratively whenever necessary. Roundtrip engineering will be used to keep the code synchronized with the design.

3.5.5 PRIMA astrometry data reduction library

Description

For the final milestone, based on the design the whole system will be coded. The application (Pipeline) algorithms will be coded in ANSI C using the ESO Common Pipeline Library and integrated into the ESO pipeline based on the recipe and procedural design.

In parallel Java template code for the IDAF will be generated from the UML design using the CASE tool. Further coding on the IDAF will follow this template code and the design will be updated iteratively whenever it does not meet anymore the current requirements.

To facilitate further discussion, we define the term IDAF as:

- An interactive environment;
- Which has dedicated user interfaces;
- Which has dedicated visualization tools;

- Which has dedicated trend finding algorithms;
- Which makes use of the PRIMA Astrometric Data Reduction Library, including:
  - The Database;
  - The scientific recipes;
  - The quality control recipes.

Specific tasks

1. Code
   (a) A library of scientific algorithms, which includes:
      i. Static database, database access tools, and archive;
      ii. Calibration engine, calibration matrix;
      iii. Scientific recipes (e.g. to correct for dispersion, chromatic effects, elevation);
      iv. Quality control recipes.
   (b) Simulated data.
   (c) A database of engineering and compressed scientific data;
   (d) A support library with general numerical computation algorithms (fitting, fourier transformations, integration, differentiation, interpolation, peak search, etc.);
   (e) The integration of the scientific algorithms in the ESO pipelines;
   (f) A fully working IDAF in which the scientific algorithms are integrated.
2. Documentation
   (a) User and maintenance manual for the ESO pipeline;
   (b) User and maintenance manual for the IDAF;
   (c) Updated design document of the IDAF;
   (d) Interface control document describing the calibration method for the pipeline;
   (e) Online reference documentation for the source code, which is auto-generated from source code with documentation tools as doxygen and javadoc.
3. Tests
   (a) Tests (performance and debugging) of the ESO pipeline with simulated data;
   (b) Tests (performance and debugging) of the DAF with simulated data.

3.5.6 Excluded tasks

Tasks excluded for this deliverable are:

- Estimate of errors due to a specific effect (PRIMA Astrometry error budget);

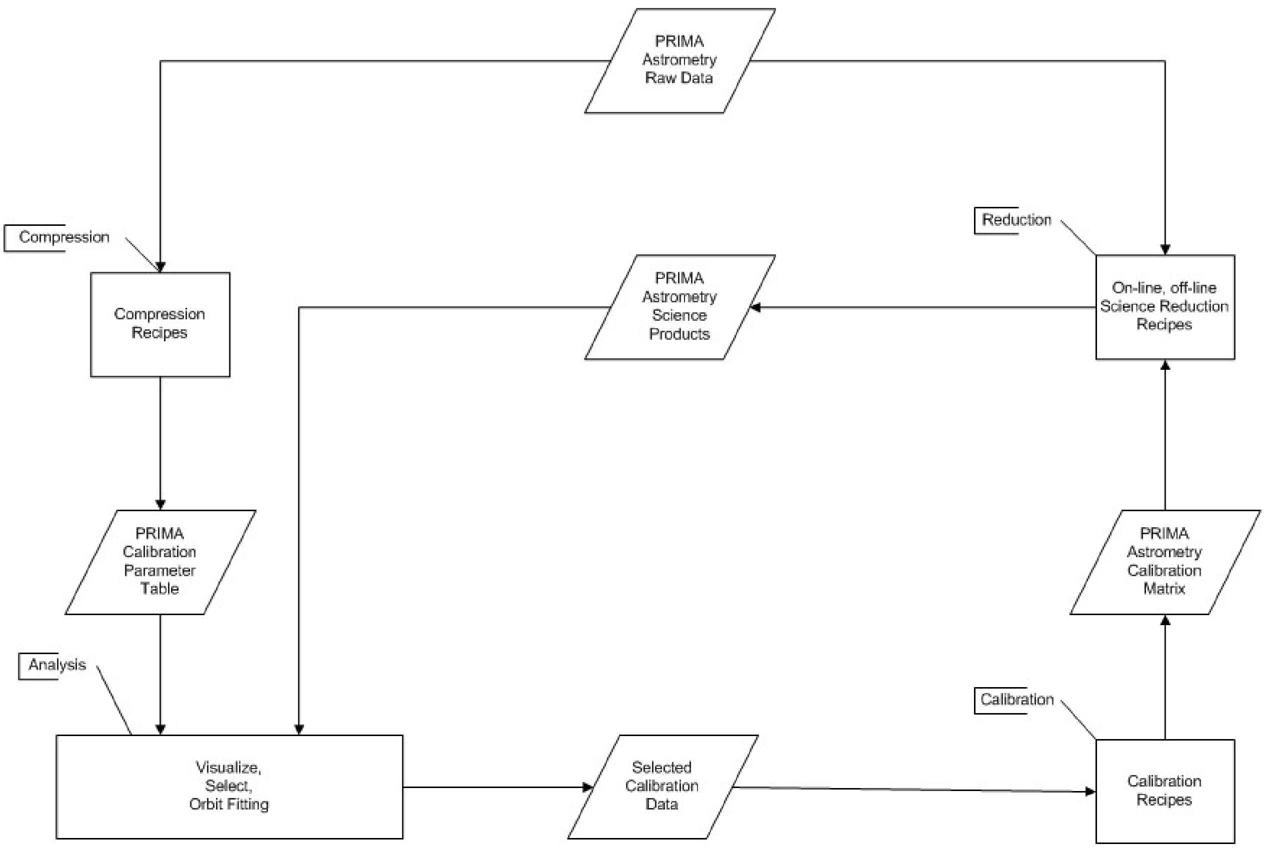

Figure 3.6: Flow diagram of the library modules.

3.5.7 Dependencies

For the preparation of the Specifications document input will be required from:
PRIMA astrometry error budget
calibration and observation strategy

In turn, the specifications will provide input to:
data reduction design

For the preparation of the design document input will be required from:
data reduction library specifications document

In turn, the design phase will provide input to:
data reduction library coding

3.5.8 CDR deliverables

- Requirements on data reduction library (document, Issue 0).

3.5.9 PDR deliverables

- Performance verification matrix data reduction library (document, Issue 0)
- Requirements on data reduction library (document, Issue 1).
- Functional specifications on data reduction library (document, Issue 1)
  - Requirements on the input data streams (FSU, MET, STS, DDL, meteo data), in particular data rate, compression and data formats;
  - Requirements on output formats;
  - Requirements on any additional information that is needed (spectral energy distribution or photometry of stars, radial velocities, ...);
  - Requirements set by the error budget analysis;
  - Requirements on the database;
  - Requirements on interfaces (with Paranal, with users);
  - Requirements on the flexibility of the DRL, e.g. the capability to cope with changing data formats or the evolution of error budget;
  - Requirements on the processing time (for one observation, for the whole data-set);
  - Requirements on data flow;
  - Data analysis facility development and implementation plan (document, Issue 0).

3.5.10 FDR deliverables

- Performance verification matrix data reduction library (document, Issue 1)
- Prototypes of critical modules (software, version 0.1).
- Design of the data reduction library (document, issue 1.0):

  - A detailed description of the algorithms and reduction recipe;
  - A procedural design of the ESO pipeline;
  - A list of tools which will be used for the user interface, data handling and visualization inside the DAF;
  - A list of tools to be used for the design and development of the system;
  - The UML design of the DAF;
  - The APIs between the algorithms and the DAF;
  - The format of the input and output files for the pipeline. The input files include the raw data and the DAF calibration product;
  - The DAF database model;
  - The format of the input, configuration, intermediate and output files of the DAF;
  - Prototypes of code where applicable.

- Data analysis facility development and implementation plan (document, Issue 1).

3.5.11 IRR deliverables

At IRR demonstration (within the consortium) will demonstrate that the DAF is able to process the simulated data-sets.

3.5.12 PAE deliverables

- Code of data reduction library (software, version 1.0);
  - The pipeline library routines tested on the simulated data with the DAF environment;
- On-site implementation plan of data reduction library (document, issue 0.1);
- User manual of data reduction library (document, issue 0.1);
- Maintenance manual of data reduction library (document, issue 0.1);
- Three FITS input files, each for one epoch, which has been used for the tests (file):
  - Well know binary system (one that really exists and be used for PRIMA phase calibration) under normal atmospheric conditions;
  - One typical example from the PRIMA astrometry science program (star with a know companion), under good observing conditions;
  - One typical example from the PRIMA astrometry science program, under rather bad observing conditions;
- A test calibration matrix file to test the calibration procedure in the pipeline;
- The documentation of the pipeline.

3.5.13 Commissioning deliverables

- Source code of version 1.0 of data reduction library (software);
- Issue 1.0 of user manual (document);
- Issue 1.0 of maintenance manual (document);

3.5.14 PAC deliverables

- Source code of version 1.X of data reduction library (software);
- Issue 1.x of user manual (document);
- Issue 1.x of maintenance manual (document);
- Review on the need to issue a change request on the delivery of IDAF;
- Issue 1.0 of Functional description of calibration engine: algorithms applied;
- Issue 1.0 of Principles at the base of IDAF.

3.5.15 FAR deliverables

- Updated software modules for the pipeline will be released by the consortium on a regular basis. Between PAC and FAR the goal is to release updates every 6 months. However the implementation of these strict dates will need to be negotiated with ESO depending on the improved performance of each update, in relation to the required efforts to update the pipeline and reprocess all available data;
- Source code of version 1.y of Data Reduction Library (software);
- Issue 1.y of user manual (document);
- Issue 1.y of maintenance manual (document);
- Issue 1.x of Functional description of calibration engine: algorithms applied;
- Issue 1.x of Principles at the base of IDAF.

3.5.16 Interfaces between consortium and ESO

For the successful completion of the PRIMA Data Reduction Library, access to PRIMA Astrometry, and participation in the PRIMA commissioning need to be defined.

Access to PRIMA astrometry data

In this proposal, the Data Reduction Library (and the associated efforts needed for development) are based on restricted access to PRIMA Astrometry data. The **raw data** available to the consortium includes:

- PRIMA astrometry scientific data from the consortium GTO program;
- PRIMA astrometry data of calibrators;
- PRIMA astrometry data of verification sources;
- PRIMA astrometry data of instrumental calibrators;
- PRIMA astrometry engineering data;
- PRIMA astrometry data obtained during commissioning, Paranalization, and technical time.

The data not available to the consortium includes:

- PRIMA Astrometry scientific data obtained through open time proposals, not related to the consortium.

Based on the raw data available by the consortium, the IDAF will allow to identify trends. These trends will be defined, and the Calibration Engine includes algorithms that computes a calibration matric to correct for these trends.

Since some of the PRIMA Astrometry scientific data may contain scientific scenarios not being covered by the data available to the consortium (e.g. fast rotating binary, very hot star), the Calibration Engine may not be able to correct trends which are very specific to these data-sets.

If during the duration of the project, there seems to be a clear need that PRIMA Astrometry data obtained through Open Time Proposals should be included in the IDAF, the consortium or ESO can make a change request to the consortium agreement.

Participation in PRIMA commissioning

Up to the PRIMA Astrometry commissioning phase, information on the PRIMA Astrometry error tree will be largely based on postiori knowledge of the system. This phase should be as short as possible, and the consortium should have access to raw PRIMA astrometry data starting at first light of PRIMA. Additionally the consortium should actively participate in commissioning of PRIMA. Also during the phase that the facility is being commissioned with the main delay lines as differential delay lines.

Data products for community

This proposal is based on the assumption that the non-interactive pipeline, with the use of the latest calibration engine parameter file, will deliver scientific grade output. This will allow ESO to provide to astronomer with PRIMA astrometric data, the raw data and the scientific grade data from the pipeline.

If after a change request from ESO or the consortium, the consortium has access to all PRIMA astrometric data, the data reduction package (which includes the pipeline library) will allow to provide raw and scientific grade data to the observers. In this case only in exceptional cases would an astronomer have to reduce his own data.

3.5.17 Long-term maintenance of data reduction library

All software development will be under the responsibility of the consortium up-to Final Acceptance Review, after which the maintenance and further development will be an ESO responsibility.

The only possible exception could be the Interactive Data Analysis Facility (which includes the user interfaces, visualization and trend analysis tools). The consortium will maintain this software till the end of the consortium guaranteed science program as this software can only be properly developed when a full data-set covering multiple years is available.

Appendix A

Preliminary PRIMA astrometry error budget

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
1.0 Zero mean stochastic (random) effects		
All decreased when observing time is increased		
1.1 Random errors with zero mean with timescales smaller than one night (i.e. error averages out substantially during one night)		
1.1.1 Air turbulence above the telescopes combined with vertical temperature or humidity gradients		1
Error depends on:		
Strength of refractive index fluctuations		
Height distribution of turbulent layers		
Separation of stars		
Timescale for fluctuations		
Outer scale (inner scale probably not relevant)		
Power spectrum index for fluctuations		
1.1.2 Air turbulence in non-common path through instrument		~ 100 if airflow through ducts; < 1 if ducts sealed
Error depends on:		
Strength of refractive index fluctuations		
Timescale for fluctuations		
Inner scale of turbulence particularly for metrology beams		
Outer scale		
Power spectrum index for fluctuations		
Spatial separation of non-common path		
Difference in wavelength between metrology and science beams		
1.1.3 Refractive index variation in common path through instrument		<1
Error depends on:		
Difference in wavelength between metrology and science beams		

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
1.1.4 Detector readout noise, photon shot noise and scintillation		
1.1.4.1 Active tracking mode		<1
Error depends on:		
Stellar flux in observing bandpass		
Transmission of optics		
Detection efficiency		
Coherence volume $r_0^2 \times t_0$		
Detector readout noise also depends on readout rate		
Scintillation also depends on structure of atmospheric turbulence and aperture diameter		
1.1.4.2 Passive ("blind") tracking mode – M is secondary star K-band magnitude		$\sim 10^{\left(\frac{M-13}{2.5}\right)}$
Error depends on:		
Stellar flux in observing bandpass		
Transmission of optics		
Detection efficiency		
Detector readout noise also depends on readout rate		
Scintillation also depends on structure of atmospheric turbulence and aperture diameter		
1.1.5 OPD errors introduced by vibration		
1.1.5.1 Vibrations in Auxiliary Telescope optics		
1.1.5.2 Vibrations in main delay line optics		
1.1.5.3 Vibrations in differential delay line optics		
1.1.5.4 Vibrations in beam combination optics		
1.1.6 Zero mean fluctuations in image plane optical surfaces		
1.1.6.1 Variation in star separator optics due to temperature correction control loop		

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
1.1.6.2 Variation in star separator optics due to wind loading		
1.1.6.3 Change in variable-curvature mirrors due to temperature correction control loop		
1.1.6.4 Change in variable-curvature mirrors due to pressure correction control loop		
1.1.6.5 Creep in variable-curvature mirror		
1.1.7 Zero mean fluctuations in pupil plane optical surfaces		
1.1.7.1 Drift in Auxiliary Telescope focus and correction		
1.1.7.2 Rotation of primary mirror due to wind loading		
1.1.7.3 Lateral motion of primary mirror due to wind loading		
1.1.7.4 Curvature variation of primary mirror due to wind loading		
1.1.7.5 Rotation of secondary mirror due to wind loading		
1.1.7.6 Lateral motion of secondary mirror due to wind loading		
1.2 Random errors with zero mean with timescales larger than one night (so many nights of observing may be required to understand these errors)		
1.2.1 Effect of air refractive index gradients within the instrument		
1.2.1.1 Auxiliary Telescopes		
1.2.1.1.1 Temperature gradient in star separator		
1.2.1.1.2 Humidity gradient in star separator		
1.2.1.1.3 Temperature gradient after star separator		
1.2.1.1.2 Humidity gradient after star separator		
1.2.1.2 Interface between Auxiliary Telescope and tunnel		
1.2.1.2.1 Horizontal temperature gradient		
1.2.1.2.2 Horizontal humidity gradient		
1.2.1.2.3 Horizontal pressure gradient (air deceleration)		
1.2.1.3 Tunnels from delay lines to Auxiliary Telescopes		
1.2.1.3.1 Horizontal temperature gradient		
1.2.1.3.2 Horizontal humidity gradient		
1.2.1.4 Delay line tunnel		

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
1.2.1.4.1 Difference between vertical temperature gradients beside external and internal walls		
1.2.1.4.2 Difference between vertical humidity gradients beside external and internal walls		
1.2.1.5 Interface between delay line tunnel and instrument laboratory		
1.2.1.5.1 Horizontal temperature gradient		
1.2.1.5.2 Horizontal humidity gradient		
1.2.1.6 Instrument laboratory		
1.2.1.6.1 Horizontal temperature gradient		
1.2.1.6.2 Horizontal humidity gradient		
1.2.2 Baseline geometry – Determined from VLBI software such as the USNO CALC package		
1.2.2.1 Differential motions between telescope station positions		
1.2.2.1.1 Error in body tide ("Earth tide") from CALC software		
1.2.2.1.2 Error in effect of Pacific Ocean tides given by CALC software		
1.2.2.1.3 Effect of fluctuations in soil humidity		
1.2.2.1.4 Diurnal temperature fluctuations		
1.2.2.1.5 Annual temperature fluctuations		
1.2.2.1.6 Variation in gravitational load on mountain		
1.2.2.2 Differential motions within telescope		
1.2.2.2.1 Difference between distortions in two telescope structures		
1.2.2.2.2 Differential wind loading		
1.2.2.2.3 Difference between principle rotation axes for telescopes		
1.2.2.3 Accuracy of baseline solutions from calibrator stars		
1.2.2.4 Accuracy of CALC Earth rotation and nutation mode		

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
1.2.2.4.1 Seasonal variations of Earth rotation from CALC model		
1.2.2.4.2 Variations on 11 year (solar) cycle		
1.2.2.4.3 El Niño years		
1.2.3 Image plane optics in cats-eye reflector		
1.2.3.1 Systematic drift in differential OPD from cats-eye reflector		
1.2.4 Variation in length calibrations		
1.2.4.1 Variation in metrology laser frequency		0
1.2.4.1.1 Variation in laser frequency with temperature		0
1.2.4.1.2 Variation in laser frequency with pressure		0
1.2.4.1.3 Variation in laser frequency with humidity		0
1.2.4.1.4 Variation in laser frequency with supply voltage		0
1.2.4.2 Error in position of air/vacuum interface in differential delay line		
1.2.4.2.1 Dependence of position error on temperature		
1.2.4.2.2 Dependence of position error on pressure		
1.2.4.3 Error in air dispersion between 1.7 microns and 2.2 microns wavelength		
1.2.4.3.1 Error in air pressure measurement		
1.2.4.3.2 Error in air temperature in ATs		
1.2.4.3.3 Error in humidity in ATs		
1.2.4.3.4 Error in air temperature in interface between AT and tunnel to main delay line		
1.2.4.3.5 Error in humidity in interface between AT and tunnel to main delay line		
1.2.4.3.6 Error in air temperature in tunnel to main delay line		
1.2.4.3.7 Error in humidity in tunnel to main delay line		
1.2.4.3.8 Error in air temperature in interface between AT tunnel and main delay line		

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
1.2.4.3.9 Error in humidity in interface between AT tunnel and main delay line		
1.2.4.3.10 Error in air temperature in main delay line		
1.2.4.3.11 Error in humidity in main delay line		
1.2.4.3.12 Error in air temperature in interface between main delay line and instrument laboratory		
1.2.4.3.13 Error in humidity in interface between main delay line and instrument laboratory		
1.2.4.3.14 Error in air temperature in instrument laboratory		
1.2.4.3.15 Error in humidity in instrument laboratory		
1.2.4.3.16 Error in formula for refractive index of air between 1.7 microns and 2.2 microns		
1.2.4.3.17 Error in formula for refractive index of airbourne water vapour between 1.7 microns and 2.2 microns		
2.0 Systematic effects (non-zero mean)		
These errors are systematic, and data from many weeks of observing must be compared in order to determine the size of any residuals		
2.1 Galactic effects		
2.1.1 Perspective acceleration due to proper motion of star		
2.1.2 Correolis effect for rotating frame of reference defined by two reference stars		
2.2 Solar system effects		
2.2.1 Relativistic effects on light path to Earth		
2.2.1.1 Velocity of Paranal relative to Solar System centre	1000	0
2.2.1.2 Gravitational influence of Sun	5	0
2.2.1.3 Gravitational influence of major planets	5	0
2.3 Atmospheric effects		

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
2.3.1 Systematic horizontal gradients in the atmosphere (probably towards Pacific Ocean)		
2.3.1.1 Temperature gradient	200	50†
2.3.1.2 Humidity gradient	100	30
2.3.1.3 Pressure gradient (wind acceleration/deceleration)	10	2
2.3.2 Curvature of isodensity surfaces in atmosphere		
2.3.2.1 Curvature of isodensity surfaces due to curvature of Earth	100	0
2.3.2.2 Curvature of isodensity surfaces due to local gravitational anomalies	10	5
2.3.3 Atmospheric dispersion/refraction		
2.3.3.1 Effect of colour difference between stars through bandpass – R is spectral resolution of FSU, currently 5	$\frac{20000}{R^2}$	$\frac{4000}{R^2}$ †
2.3.3.2 Error in knowledge of bandpass – R is spectral resolution of FSU	$\frac{2000}{R^2}$	$\frac{400}{R^2}$
2.3.3.3 Error in knowledge of local atmospheric conditions	50	
2.3.3.4 Dependence on three-dimensional atmospheric structure (terms not included in 2.3.1 and 2.3.2)	50	
2.3.3.5 Dependence on elevation difference between stars	100	10
2.4 Differential OPD from optical components		
2.4.1 Image plane optics in star separator		
2.4.1.1 Differential OPD from optical misalignment in single star calibration mode		
2.4.1.2 Differential OPD from atmospheric angle refraction in single star calibration mode		
2.4.1.3 Differential OPD from resolved structure in single calibrator star		
2.4.2 Differential OPD from position offset between collimated beams for single star calibration mode and science targets		
2.4.2.1 Position offset between collimated beams for single star calibration mode and science mode		

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
2.4.2.1.1 Dependence of position offset on colour of single calibration star		
2.4.2.1.2 Dependence of position offset on elevation of single calibration star		
2.4.2.1.3 Dependence on atmospheric r_0 (perhaps best to use simulations)		
2.4.2.1.4 Dependence on outer scale of atmospheric turbulence		
2.4.2.1.5 Dependence on temperature		
2.4.2.1.6 Dependence on humidity		
2.4.2.1.7 Dependence on pressure		
2.4.2.2 RMS wavefront error from pupil plane optics		
2.4.2.2.1 RMS wavefront error from pupil plane optics in AT after star separation		
2.4.2.2.2 RMS wavefront error from pupil plane optics between AT and main delay line		
2.4.2.2.3 RMS wavefront error from pupil plane optics in main delay line		
2.4.2.2.4 RMS wavefront error from pupil plane optics between main delay line and differential delay line		
2.4.2.2.5 RMS wavefront error from pupil plane optics in differential delay line		
2.4.2.2.6 RMS wavefront error from pupil plane optics between differential delay line and beam combiner		
2.4.2.2.7 RMS wavefront error from beam combiner optical surfaces		
2.4.2.3 Differential OPD resulting from 2.4.2.1 and 2.4.2.2 combined		
2.4.3 Differential OPD from angle offset between collimated beams for single star calibration mode and science targets		

		Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
	2.4.3.1 Angle offset between collimated beams for single star calibration mode and science mode		
	2.4.3.1.1 Dependence of angle offset on colour of single calibration star		
	2.4.3.1.2 Dependence of angle offset on elevation of single calibration star		
	2.4.3.1.3 Dependence on atmospheric r_0		
	2.4.3.1.4 Dependence on outer scale of atmospheric turbulence		
	2.4.3.1.5 Dependence on temperature		
	2.4.3.1.6 Dependence on humidity		
	2.4.3.1.7 Dependence on pressure		
	2.4.3.2 RMS wavefront error from image plane optics		
Needs to be broken down into individual mirrors	RMS wavefront error from image plane mirror in main delay line cats-eye		
	RMS wavefront error from image plane mirror in differential delay line cats-eye		
	RMS wavefront error from image plane optics in AT after star separation		
	Distance of mirrors from pupil plane		
	RMS wavefront error from image plane optics between AT and main delay line		
	Distance of mirrors from pupil plane		
	RMS wavefront error from image plane optics in main delay line		
	Distance of mirror from pupil plane		
	RMS wavefront error from image plane optics between main delay line and differential delay line		
	Distance of mirrors from pupil plane		
	RMS wavefront error from image plane optics in differential delay line		

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
Distance of mirrors from pupil plane		
RMS wavefront error from image plane optics between differential delay line and beam combiner		
Distance of mirrors from pupil plane		
RMS wavefront error from beam combiner optical surfaces		
2.4.3.3 Differential OPD resulting from 2.4.3.1 and 2.4.3.2 combined		
2.4.4 Differential OPD from optics before the star separator		
2.4.4.1 Difference in position of beam footprints on Auxiliary Telescope M1		
2.4.4.2 RMS wavefront error introduced by M1		
2.4.4.3 Difference in position of beam footprints on Auxiliary Telescope M2		
2.4.4.4 RMS wavefront error introduced by M2		
2.4.4.5 Difference in position of beam footprints on Auxiliary Telescope M3		
2.4.4.6 RMS wavefront error introduced by M3		
2.4.4.7 Difference in position of beam footprints on Auxiliary Telescope M4		
2.4.4.8 RMS wavefront error introduced by M4		
2.4.4.9 Difference in position of beam footprints on Auxiliary Telescope M5		
2.4.4.10 RMS wavefront error introduced by M5		
2.4.5 Systematic differences in baseline length for different stars		
2.4.5.1 Difference in effective baseline length for split single star and dual star observations		
2.4.5.2 Dependence of effective baseline length on colour of star		
2.4.6 Systematic phase errors in FSU		

	Effect (nm OPD)	"Easily" calibrated to an accuracy of (nm OPD)
2.4.6.1 Dependence of systematic phase bias on brightness of target		
2.4.6.2 Dependence of systematic phase bias offset in position of collimated beam		
2.4.6.3 Dependence of systematic phase bias offset in angle of collimated beam		
2.4.6.4 Cyclic errors in FSU		

Table A.1: Error terms for differential astrometry – the two terms of most concern at present are marked with a † symbol.

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