Data Flow System for the Very Large Telescope Interferometer

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ABSTRACT

The Data Flow System is the VLT end-to-end software system for handling astronomical observations from the initial observation proposal phase through the acquisition, processing and control of the astronomical data. The VLT Data Flow System has been in place since the opening of the first VLT Unit Telescope in 1998. When completed the VLT Interferometer will make it possible to coherently combine up to three beams coming from the four VLT 8.2m telescopes as well as from a set of initially three 1.8m Auxiliary Telescopes, using a Delay Line tunnel and four interferometry instruments. The Data Flow system is now in the process of installation and adaptation for the VLT Interferometer. Observation preparation for a multi-telescope system, handling large data volume of several tens of gigabytes per night are among the new challenges offered by this system. This introduction paper presents the VLTI Data Flow system installed during the initial phase of VLTI commissioning and discusses the first experiences with this system. Observation preparation, data archival, and data pipeline processing are addressed.

Keywords: Very Large Telescope, Interferometer, Data Flow System, Data Handling

1. INTRODUCTION

The fourth 8.2m telescope of the Very Large Telescope (VLT) Observatory on Cerro Paranal (2635m) in Northern Chile has been commissioned for operations at the end of the year 2000. During the same year, the Paranal observatory has been equipped with optical Delay Lines installed in an underground Delay Line tunnel with optical entries for the beams coming from each Unit Telescope (UT) of diameter 8.2 meter as well as from movable Auxiliary Telescopes (AT) of diameter 1.8 meter. Eight Delay Lines in the scheme have optical entries in the Delay Line tunnel. By combining the light from two or three telescopes taken among the four Unit Telescopes and the three initially available Auxiliary Telescopes, different configurations are reached corresponding to a given baseline vector. With a maximum baseline length of 202 meters, the VLT Interferometer makes it possible to reach high angular resolution of the order of a few milliarcseconds. In March 2001, first fringes [2] have been obtained with the VLT Interferometer using the test instrument VINCI [3]. Three more instruments will be active at the VLT Interferometer, providing capabilities for coherent combination in the mid-infrared wavelength domain with MIDI, up to three near-infrared optical beams with AMBER, and simultaneous interferometric observations of two objects with PRIMA.

The Data Flow System [4] is the VLT end-to-end software system for handling astronomical observations from the initial observation proposal phase through the acquisition, processing and control of the astronomical data. The operations model of the VLT allows principal investigators to apply for visitor-mode or service-mode observation programs. In visitor mode, the astronomer is present at the telescope and can adapt the observation program to specific target properties, changing observation conditions, or calibration needs. In service-mode the observatory scientific operators perform the observations and the data are processed and sent to the requesting astronomer. The service mode [1] has been supported at the VLT since the beginning of operations with the first telescope ANTU in 1998. Most observations in

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interferometry will involve measurements for different spatial frequencies and are likely to require different configurations and spread over periods of several weeks. It is therefore expected that service observation will be a dominant mode at the VLTI. This paper presents the VLTI Data Flow system installed during the initial phase of VLTI commissioning. Observation preparation, data archival, and data pipeline processing are addressed.

2. THE DATA FLOW CONCEPT

The procedure for proposal preparation in the Data Flow System [4] involves a Phase I and a Phase II proposal preparation. In Phase I, proposals are submitted electronically to ESO and evaluated by the Observing Program Committee (OPC). After the OPC selection has taken place, Phase II preparation is based on the creation of Observation Blocks. Each Observation Block specify an individual observation sequence which can be scheduled and executed completely without interruption. Observation Blocks are created by specifying the template parameters, target information, and user-defined scheduling constraints. The user will be assisted in these phases by a User Support Astronomer and by observation preparation tools. These tools include generic systems like finding chart generators or guide star selection systems, and instrument related tools like exposure time calculators (ETCs). Feasibility checks of the proposals are performed by the observatory and include technical feasibility and exposure time control.

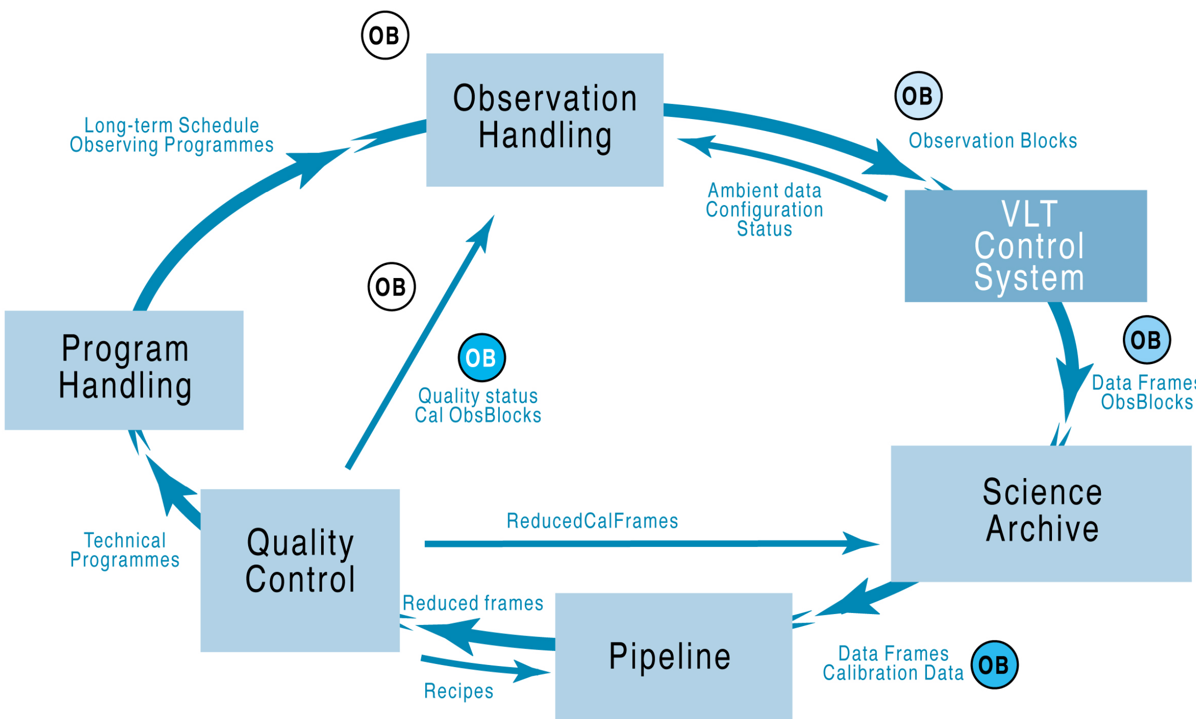

Figure 1: Schematic view of the VLT Data Flow System

The Observation Blocks are queued for service-observing and organized in a schedule managed on a long-, medium-, and short-term basis. In Service Mode the constraint set defined by the user during phase 2 preparation is compared to the ambient data during the execution of observations, hence providing a better flexibility regarding the optimal execution of an observation. The other mode of observation is the Visitor mode, during which the astronomer attends at the observatory the execution of observation and makes use of the on-line pipeline.

Upon execution of the OBs, the data produced are stored first in an on-line archive system at Paranal observatory, then in the VLT archive in Garching. The Science Archive stores all raw frames produced by the instruments, as well as reference calibration data, and log files including maintenance and ambient conditions logs. The Science Archive is available to archive researchers and astronomers for catalog access and retrieval of scientific data as they become available after the end of the proprietary period, as well as retrieval of calibration data as soon as they have been processed and verified by the Data Flow Operations.

A data reduction pipeline is available at the telescope for immediate quality assessment of the data, and in Service mode the data are reprocessed in Garching before being controlled by a Quality Control Scientist and being sent to the user. The VLT Data Flow System has been in place since the opening of the first VLT Unit Telescope in 1998. The scheme is now in the process of installation and adaptation for the VLT Interferometer.

3. VERY LARGE TELESCOPE INTERFEROMETER

The VLT Delay Lines form an essential part of the VLT Interferometer [5] (VLTI). In order to enable a coherent combination[10] of the light beams from the individual telescopes of the VLT (that is, to produce interferometric fringes at the focal point), the optical path differences (OPD) must be compensated by the Delay Line system to a precision in the order of a fraction of the coherence length. Each VLTI Delay Line consists of a retro-reflector mounted on a moving carriage. The optical design of this “Cat's Eye” is of the Ritchey-Chretien type that reflects the light very effectively. For this particular application, the “Cat's Eye” is not a corner cube with 3 perpendicular mirrors as is the case in the reflectors on cars and bicycles. It is in fact a telescope with a variable curvature mirror at the focus that sends a light beam back in a direction parallel to the one it came from. The moving base enables the Cat's Eye to travel along a 60 meters long rail track, thereby providing optical path difference corrections of up to 120 meters, as required for the VLTI array configurations at Paranal.

Although the ultimate sensitivity of the VLTI will be obtained when combining the VLT 8.2-m telescopes, the Auxiliary Telescopes constitute an essential element of the VLTI for the following reasons:

- The ATs will make it possible to perform full testing and commissioning of the second generation of VLTI instruments, without having to make use of valuable light from the 8.2-m telescopes.
- The ATs will provide the best imaging capability of VLTI by complementing the array of the four 8.2-m telescopes. The ATs can be placed on any of 30 possible stations and therefore provide many interferometric baselines. This will make interferometric imaging possible.
- The ATs provide the longest possible baseline of the VLTI (202 meters), fully utilizing the restricted space available on the Paranal mountain platform
- The ATs will enable full time use of the VLTI facilities. They are 100% dedicated to VLTI, while the 8.2-m UTs will be only intermittently available for interferometric observations.
- The ATs do not need adaptive optics correction in the mid-infrared at 10 microns and are nearly corrected in the near-infrared.

To commission the Cerro Paranal VLTI complex even before the availability of ATs, ESO decided to build two dedicated light collectors (the VLTI siderostats) and a specific beam combiner instrument (VINCI). The latter is based on the proven concept of FLUOR (Fiber Linked Unit for Optical Recombination) which has been operated since 1995 as a focal instrument of the IOTA interferometer in Arizona. Later, it was decided to extend the capabilities of VINCI to provide an artificial star and an alignment verification unit. This extended instrument is called LEONARDO da VINCI (LdV), while the name VINCI is still used in the beam combiner part.

MIDI will be the first scientific instrument installed at the VLTI. It will cover the mid-infrared range between 10 and 20 microns. It records spectrally dispersed fringes and can reach at 10 µm a resolution of the order of 20 milliarcsecond. The expected limiting magnitude is N = 5 mag (400 mJy) in self-fringe-tracking mode, with 8 m telescopes and tip/tilt correction, and N = 11.5 mag (1 mJy) with external fringe tracking The actual design of MIDI is optimized for operation at 10 µm and a possible extension to 20 µm is considered. The main scientific objectives are very embedded young stars and protostars, the study of circumstellar disks, the search for exoplanets, the study of brown dwarfs, active galactic nuclei dust tori and the center of our own galaxy.

AMBER will combine up to three beams to be the first VLTI instrument with some imaging capability. It delivers spectrally dispersed fringes covering the three near-infrared bands J, H, K. Three spectral resolutions of approximately

35, 1000, 10000 are supported. By analysing three beams at once it is possible to obtain images through phase closure techniques eliminating the influence of atmospheric turbulence on fringe position. The system can also be used in differential interferometry mode in order to estimate the phase difference between two spectral channels. The wavelength coverage will be extended in a second phase down to 0.6 µm at the time the ATs become operational. The magnitude limit of AMBER is expected to reach K ≅20 when a bright reference star is available and K ≅14 otherwise. The main scientific objectives are the investigation at very high angular resolution of disks and jets around young stellar objects, active galactic nuclei dust tori, the search for exoplanets, the study of stellar properties such as diameter, pulsation, mass loss, with a spectral resolution up to 10000.

The objective of PRIMA is to enable simultaneous interferometric observations of two objects - each with a maximum size of 2 arcsec - that are separated by up to 1 arcmin, without requiring a large continuous field of view. PRIMA can be subdivided into five sub-systems that are positioned in different locations of the VLTI. PRIMA is composed of a star separator that feeds two arbitrary objects into the Delay Lines, a laser metrology system to monitor the internal OPD between object and reference star, a differential Delay Line to adjust the OPD between object and reference star, a fringe sensor unit, and an astrometry detector allowing the observation of the fringe patterns of both stars on the same detector.

4. OBSERVATION CONSTRAINTS IN INTERFEROMETRY

One of the major problems to overcome for interferometric observations is to efficiently cancel the optical path differences between the different beams[10]. These differences are caused by:

- the static geometric path difference between the telescopes in a certain configuration;
- the diurnal motion of the astronomical source during observation due to Earth's rotation; and
- the rapid path variations due to atmospheric disturbances and/or mechanical vibrations along the optical path.

The transfer function of an interferometer varies rapidly with a time scale of a few minutes. It is therefore necessary to perform alternate exposures on science targets and calibrators with the telescopes. Calibrators are either unresolved stars or stars whose diameters are known to a good accuracy. This sequence of observations must be executed in its entirety for the data to be scientifically useful. The transfer function of the instrument is interpolated with respect to time between the calibration exposures before being applied to the scientific target.

As we see the first observation constraint will be the possibility to perform alternate exposures of science and calibrator objects with a minimum time overhead between the targets. All targets must be observed within the finite stroke of the Delay Lines. The Delay Line speed depends on the position of the target in the sky, the speed reversing sign when the target passes perpendicular to the baseline. Among the observation constraints, the most relevant parameter for interferometry may be the sidereal time, which will determine the projected baseline of a given object, and therefore the coverage in the spatial frequency spaces. Most observations in interferometry will involve measurements for different spatial frequencies and are likely to require different configurations and spread over periods of several weeks. It is therefore expected that service observation will be a dominant mode at the VLTI.

The geometrical constraints on the observation of the science and calibrator targets, the limited observability of the objects due to both the range of Delay Lines and shadowing effects will make it necessary to assess the technical feasibility of observations at both stages of phase 1 and phase 2 preparation. During phase 1, general tools like the web based exposure time calculators will be provided. In phase 2, all details of the observation are provided and can be validated more accurately.

5. OBSERVATION PREPARATION TOOLS

Observation preparation tools have been provided for the VLT instruments in the form of Exposure Time Calculators (ETC) accessible over the Internet (http://www.eso.org/observing/etc). The system provides a uniform access to the ETCs provided for the different VLT instruments. Several solutions have been designed to make it possible to efficiently develop and maintain these applications: HTML templates and dictionaries are used to generate the pages on the fly, a CGI scripting languages is used for prototyping and a database system simplifies the adjustment of instrument characteristics. The same concept will be applied as much as possible for the VLTI observation preparation tools[6]. These include in addition to ETCs for the different VLTI instruments a visibility calculator and constraint checker. A number of observation constraints must be taken into account for the preparation of interferometry observation.

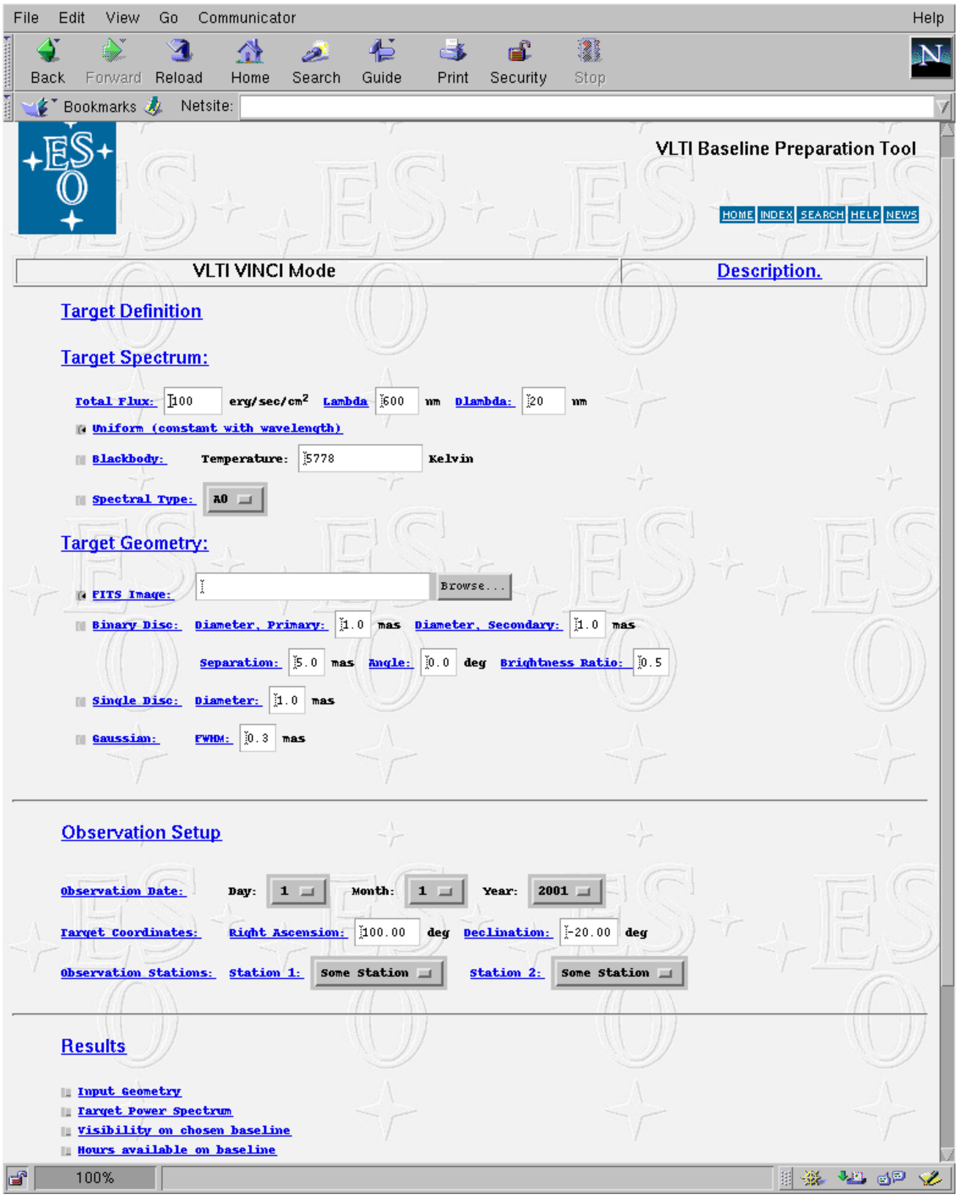

Figure 2: The VLTI Visibility Calculator (preliminary design)

With the longest VLTI baseline (202 m), angular resolutions can be measured at the scale of one milliarcsec (1 mas). Unresolved objects, namely objects much smaller than the 1 mas limit, will yield maximal visibility. The fringe visibility decreases with the angular size of the observed target. The VLTI Visibility Calculator computes the fringe visibility as a function of the object diameter, the position of the target in the sky at the time of the observation, and the selected configuration. It takes into account the horizon map of the observatory and shadowing effects induced by telescope domes and structures on the observatory platform. It computes the optical path length, the optical path difference, and takes into account the range of the Delay Lines to estimate the period of observation for a given target.

The ETC takes into account the spectral energy distribution of an object, the transmission curves and dispersions of an instrument, as well as the instrument configuration to compute the signal-to-noise ratio and inversely the exposure time required to obtain a given signal-to-noise ratio on the fringes.

In the Data Flow system, the instrument parameters are grouped in high level structures called Templates and Observation Blocks in the VLT Data Flow terminology. The Template activates a standard operation mode of an instrument, for instance for the purpose of internal calibration, observation of calibration objects, or scientific observations. The Template signature includes the list of instrument parameters. Templates are grouped in Observation Blocks, which in the Data Flow correspond to an unbreakable unit of observation. Templates and Observation Blocks are assembled with P2PP, the Phase 2 Proposal Preparation tool. This Java tool provides a uniform graphical user interface to all VLT and VLTI instruments. In visitor modes the OBs are loaded using P2PP directly at the VLTI. In service mode, the OBs are ingested in a repository in Garching. It is then transferred to the observatory by means of a replication server. Science Operations staff organize the OBs for the coming nights and execute them as conditions permit.

6. OBSERVATIONS AND DATA HANDLING

The data produced by the instrument are transferred to the on-line archive system (OLAS), responsible for the short-term data storage and data distribution. OLAS delivers the data files to the archive storage system (ASTO) for archive media production. It also transfers the data to the pipeline as well as to the off-line workstation where the user can retrieve raw and reduced data. OLAS is also responsible for ingesting a summary information of the data files in a relational (Sybase) database, which is replicated to the central archive in Garching. The archive media produced by ASTO (now DVDs) are shipped to ESO Garching. Following some consistency checking it is transferred to the central on-line science archive. Internal and external users can query the ESO science archive and data are shipped to authorized users upon request. In addition to the scientific data, the science archive provides also permanent storage and access to the operational logs database.

The data rate for the first VLTI instrument VINCI is less than 1 gigabyte per night. The data rates will be higher for AMBER (0.7 MB/s) and MIDI (2.3 MB/s). For MIDI this translates into more than 40 gigabytes of data per night. The handling of such data volumes pushes the current system to its limits, in terms of overall throughput. For example, the DVD production is limited by the media capacity and writing speed. For this reason a new archive technology, based on magnetic disks rather than DVDs, is being evaluated and seems quite promising.

Interferometry data are usually stored in the form of binary tables, since in most cases only a fraction of the detector is used to read the data. Several discussions are still taking place in the interferometry community for the definition of a general data structure within the FITS standard. The header of the data follows the ESO Data Interface Control guidelines and provides the FITS keywords necessary for the data handling, processing, archive retrieval and proper documentation of the data.

The VLTI Data Flow System installed at Paranal observatory is composed of five workstations of type HP J5600. The instrument data are transferred from the instrument workstation to the OLAS machine, where they are kept on a safe RAID system of capacity 128 GB. The Data Handling Server (DHS) takes care of distributing the data to the pipeline, user and archive workstations. Two machines are reserved for archive operations. One is dedicated to the Sybase server, where operations critical informations are stored in various databases: the observation block repository, the database of data products generated by the instruments, the central message logging database, the database for archive files and media, etc. The other archive machine (ASTO) is dedicated to media production, in particular CDs and DVDs. The pipeline and offline workstations have similar configuration, with two disks of capacity 73GB for raw and processed data, as well as a graphic display. The pipeline workstation usually runs in automatic mode, receiving and processing the data, displaying the results, and transferring the processed data to the offline workstation. On the offline workstation, interactive tools are available for reprocessing and further analysis of the data in view of commissioning and scientific evaluation.

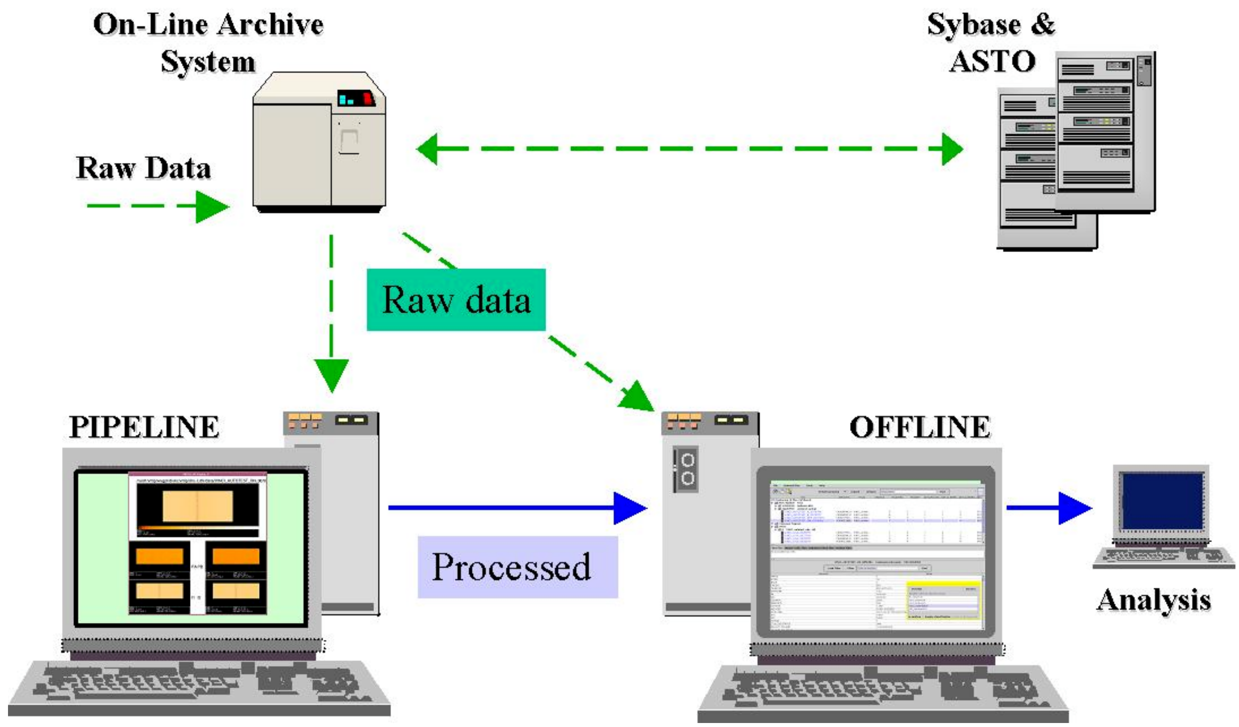

Figure 3: The present VLTI Data Flow System at Paranal

7. DATA REDUCTION PIPELINE

The pipeline receives the raw data frames from the DHS machine and classifies them according to the specifications given in the pipeline reduction rules. Conditions are evaluated on FITS keywords in order to classify the data. This determines the reduction procedure applied to the data. Before executing the procedure it may be necessary to read additional FITS keywords and to query auxiliary calibration data and tables from the pipeline local calibration database. A reduction block is prepared and sent for execution to a data reduction system. The VINCI pipeline has been operational since the VLTI first fringes in March 2001. The VINCI measurement set consists of 4 values, including the Interferometer 1, Interferometer 2, Photometer A and Photometer B measurements at a given time (also corresponding to a given OPD). A scan is a sequence of OPD variation; it typically lasts about 0.1 second with VINCI. Series of scans are taken for different optical configurations: off-source scans, telescope A only, telescope B only, and a longer sequence of scans with both telescopes on-source. An exposure with VINCI includes the set of 4 batches and all auxiliary information. Each exposure produces a FITS file containing all information necessary to derive uncalibrated visibilities.

The processing kernel of the VINCI pipeline is a set of ANSI-C procedures estimating the visibility [7] (or squared coherence factor) of the fringes. The routines are based on a few public domain libraries, in particular the CFITSIO [8] and FFTW[9] package. For the visualization of FITS binary tables the public domain tool “fv”, part of CFITSIO, is being used. The analysis of interferometry data involves two stages. First the raw visibilities are estimated on both the science and calibrator data. This is the most computing intensive step, during which science and calibrator data are processed in a similar way. In a second stage, the calibrator information is used to estimate the instrument transfer function. This transfer function is then interpolated as a function of time and the science data are corrected from it, yielding calibrated visibilities with error estimates that can be used to determine the science object parameters. The second stage of calibration involves a limited amount of data as it applies to time averaged data. It may also require user interaction for the identification and rejection of calibration points. The present VINCI pipelines performs automatically the first stage of processing and prepares FITS files containing the raw visibilities and all information required for model fitting. The pipeline generates several data products. First the photometry-corrected interferograms are delivered for the purpose of commissioning analysis. This is delivered in ASCII form for further processing. The raw visibilities, together with all information required for further astrophysical analysis, are written in a FITS file.

The Quality Control (QC) system includes the tools used inside and outside the pipeline environment in order to control the conditions in which the data have been acquired and processed, in particular the instrumental and observational conditions. Quality control parameters are measured on the data and written to log files. The QC parameters have proven a very useful method for checking and tracking the health of instruments. During the pipeline processing the data quantities characterizing the performance of the instrument are measured. These values are written to an operational log file. The log files are produced on a daily basis and can be used to produce automatic reports, graphs and summary information. The QC log files are used for diverse applications, for example to establish a catalog of observed objects, to produce trend graphs of the interferometer transfer function, or to verify the quality of the processing by checking the number of scans rejected by the pipeline.

The science VLTI instruments like MIDI will set very high requirements in terms of pipeline computation speed. Presently the VINCI pipeline can process the data at about the same rate as they are acquired, but for MIDI two order of magnitudes should be gained in the computation speed. Solutions are being investigated using large VINCI data sets and MIDI simulated data

8. OFF-LINE AND COMMISSIONING ANALYSIS

In the present phase of system commissioning, most of the calibration and analysis aims at characterizing the performance of the interferometer, using for observations two siderostats of 40cm diameter separated by 16m. In particular the interferometer transfer function, environmental parameters like the atmospheric piston noise or the level of tunnel internal seeing, opto-mechanical performance and sensitivity of the Delay Lines are being controlled. A number of stars have been measured and a major criteria for stability could be verified: The equivalent point source contrast, i.e. the interferometer transfer function, was measured to be 0.87 and to be stable to within 1% over three days what is far better than the required 5% over five hours. Other commissioning tests aim at verifying that fringes are found on any bright star in the specified field of view (60 degrees of zenith) or that low visibilities (down to 5%) can be measured. For all these tests, the pipeline provides photometry-corrected interferograms, uncalibrated visibilities, and the QC parameters which are instrumental to the assessment of the system performance. After this first-stage processing, data are transferred from the off-line workstation to the dedicated environments used for the performance analysis of each independent subsystem of the VLTI.

For the scientific analysis of data, different interactive tools are provided on the off-line workstation, written with commercial data analysis packages. The data can be browsed and organised around OB programs with the Gasgano tool, which provides means for organizing large amounts of data, classify them, view headers, and call scripts on selected files. Gasgano can be used as a front-end graphical interface to the data reduction software. Commands are provided to perform a second stage of calibration on the pipeline results. First the data are glued together and data from several consecutive nights are grouped by instrument modes. The calibration information can be tuned and the instrument transfer function is evaluated on the calibrator and interpolated with time. Finally it is possible to apply the calibration to science data and to model the intensity distribution of the source.

9. ABBREVIATIONS

AMBER	Astronomical Multi-BEam Recombiner
ASTO	Archive Storage System
AT	Auxiliary Telescope (1.8m)
DFS	Data Flow System
DHS	Data Handling System
DVD	Digital Video Disc
ETC	Exposure Time Calculator
FITS	Flexible Image Transport System

FLUOR	Fiber Linked Unit for Optical Recombination
mas	milliarcsecond
MIDI	Mid-Infrared interferometric instrument
OB	Observation Block
OPC	Observing Program Committee
OPD	Optical Path Difference
OPL	Optical Path Length
P2PP	Phase 2 Proposal Preparation
PRIMA	Phase-Referenced Imaging and Microarcsecond Astrometry
QC	Quality Control
QC1	Quality Control Level 1
RAID	Redundant Array of Independent Disks
UT	Unit Telescope (8.2m)
VINCI	VLT INterferometer Commissionning Instrument
VLT	Very Large Telescope
VLTI	Very Large Telescope Interferometer

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