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ABSTRACT

The Very Large Telescope Interferometer is one of the most proficient observatories in the world for high angular resolution. Since its first observations, it has hosted several interferometric instruments operating in various bandwidths in the infrared. As a result, the VLTI yields countless discoveries and technological breakthroughs. We introduce to the VLTI the new concept of Asgard: an instrumental suite including four natively collaborating instruments: BIFROST, a stellar interferometer dedicated to the study of the formation of multiple systems; Hi-5, a nulling interferometer dedicated to imaging young nearby planetary systems in the M band; HEIMDALLR, an all-in-one instrument performing both fringe tracking and stellar interferometry with the same optics; Baldr, a fibre-injection optimiser. These instruments share common goals and technologies. Thus, the idea of this suite is to make the instruments interoperable and complementary to deliver unprecedented sensitivity and accuracy from J to M bands. The interoperability of the Asgard instruments and their integration in the VLTI are the main challenges of this project. In this paper, we introduce the overall optical design of the Asgard suite, the different modules, and the main challenges ahead.

Keywords: integrated-optics, exoplanets, wavefront control, infrared, high contrast imaging, high angular resolution, optical fibers, long baseline interferometry

1. INTRODUCTION

The emphatic triumph of the Very Large Telescope Interferometer (VLTI) and its second-generation instruments in delivering unique science has set European astronomy apart, motivating the ongoing facility upgrade within the Gravity+ framework promising still further ground-breaking scientific discoveries. In parallel, major technology and scientific milestones have been achieved on other interferometric facilities, such as the Center for High Angular Resolution Astronomy Array (CHARA) and the Large Binocular Telescope Interferometer (LBTI). New ideas and laboratory demonstrations have also emerged in recent years opening and enabling the path to novel scientific capabilities for optical interferometry. Leveraging these recent developments, the Asgard instrument suite will extend the scientific capabilities of the VLTI with a set of four instrument modules: BIFROST[1–3] (Beam-combination Instrument for studying the Formation and fundamental paRameters of Stars and planeTary systems) which is a Y/J/H-band combiner optimized for high spectral resolution, Baldr which is an H-band

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injection optimizer for BIFROST, HEIMDALLR[4] which is a high-sensitivity K-band fringe tracker, and Hi-5[5–10] which is an L-band nuller optimized for high-contrast observations.

This paper presents the instrument capabilities and key scientific objectives of Asgard. This is a first step to add these additional scientific capabilities to the VLTI by proposing Asgard as a visitor instrument. Following the successful model of the PIONIER instrument, we plan to offer keeping Asgard on Paranal following the initial visitor mode phase, delivering benefit to a broad community for years to come and serving as a critical new platform for test and launch of future innovations.

2. SCIENCE CASES FOR ASGARD

Asgard science cases mainly revolve around multiple systems like binaries and planetary systems. It will complete the knowledge acquire with the GAIA survey on multiple systems, which represent around 28 millions of non-single stars. BIFROST will deliver information about the orbit statistics, the dynamical masses and the ages of such system thanks to its spectral and high angular resolution capabilities. It will also study the formation and evolution of binaries or planetary systems detected by GAIA by focusing on their spin-orbit alignment. Mass accretion and ejection of young stellar objects and active galatic nuclei will also be observed in Y,J and H bands to complete analyses previously carried in K band.[11–15] The advantages of observing in Y, J and H bands are the exploitation of a richer spectrum (Paγ 1.094 μm, Paβ 1.282 μm, Br6…Br12 1.73…1.55 μm, [Fe II] 1.257 μm, He I 1.083 μm), and where the Paschen lines have 4…10-times higher equivalent width then Brγ for typical young stars and AGN.[16] Asgard's off-axis fringe tracking mode will enable BIFROST to focus on exoplanet atmospheres and circumplanetary disks. BIFROST offers up to 6 times higher spectral resolution than Gravity and opens a spectral window of particular interest for line studies.

One of the purposes of Hi-5 will be to deepen the understanding on the formation of exoplanets, particularly the giant ones and constrain their properties.[17,18] Understanding their formation and evolution requires the observation and study of the transition disks with this nuller. Finally, Hi-5 will also contribute into the detection of exo-Earths. Such planets are masked and linked with the exozodiacal dust (exozodi) present in the inner regions of main-sequence planetary systems, including the Habitable Zone (HZ). Light from HZ dust adds photon noise and disk structures cause confusion.[19] Studying exozodiacal dust thus helps locate habitable planets in the Universe and understand their prevalence. Hi-5's fiftyfold SNR improvement for exozodi observations over previous instruments will allow us to finally overcome constraints from low-significance detections and small-number statistics to the point where a true exozodi luminosity function can be derived and correlated with host star and planetary system properties. Hi-5's observing wavelength critically connects the NIR and N-band detections, thus allowing for creating a unified picture of exozodiacal dust across all relevant spatial scales and observing wavelengths. Ultimately, the high SNR of the Hi-5 observations will likely allow for image reconstruction and thus the detailed study of the dust origin through its distribution and the search for structures indicative of planet-disk interaction.

3. INSTRUMENT CAPABILITIES

Asgard will extend the scientific capabilities of the VLTI in many ways: shorter wavelengths combined with high-spectral resolution, high-sensitivity and high-performance fringe tracking, and high-contrast direct imaging with the first VLTI nulling interferometer. To do so, Asgard relies on the four following instruments:

- BIFROST will offer dramatic benefits compared to the 2nd-generation VLTI instruments, namely a better angular resolution (due to shorter wavelengths), a higher continuum flux for blue sources (as we observe closer to the peak wavelength of the photosphere), around 6 times higher spectral resolution (R=25,000), and access to new line tracers, including Paβ 1.282 μm, Paγ 1.094 μm, the He I 1.083 μm accretion-tracing line,[20] and forbidden lines (e.g. [Fe II] 1.257 μm). To do so, BIFROST will have two arms: one with a low resolution (LR) spectroscope and the other one with a high resolution (HR) spectroscope.[1]

- HEIMDALLR is a dual-band and multiaxial beam combiner, where beams are placed in a two-dimensional array with zero redundancy in separation, then combined in the manner analogous to an aperture-mask interferometer. This innovation delivers: low order wavefront control by the retention of the full two-dimensional information contained in the interferogram, high sensitivity by the use of bulk optics, and accurate closure-phase using the proven concept of aperture masking interferometry.

- Baldr uses the same detector as HEIMDALLR, and provides a Zernike Wavefront Sensor or a photonic lantern to augment Naomi (in number of modes and speed) or GPAO (Gravity+ AO, in speed for low-order modes). This system determines the practical magnitude limit for BIFROST as a secondary adaptive optics system is needed to increase short-wavelength Strehl. It can operate in either J or H bands, leaving the rest of Y,J,H for BIFROST science.
- Hi-5 will be the first nulling instrument on the VLTI, the first long-baseline nuller in the Southern hemisphere, and the first operating at L band, where young giant planets are the most luminous. Leveraging the long-baseline of the VLTI and the ongoing Gravity+ facility upgrade, it will be able to directly image the snow line where most giant exoplanets are located. It relies on integrated optics for beam combination in order to provide a compact and stable design.

The main instrumental features of the VLTI Asgard science modules are given in Table 1 and the preliminary performances are given in Table 2.

Table 1. Main instrumental features of the VLTI Asgard modules

Feature	**BIFROST**	**HEIMDALLR**	**Baldr**	**Hi-5**
Photometric band	Y, J, H	K	H	L
Central wavelength (μm)	1.35	2.18	1.6	3.75
Bandwidth (μm)	0.6	0.45	0.3	0.5
Spectral resolutions	**LR arm**: R=50 **HR arm** MR: R=1000 (1.05-1.65 μm) HR: R=5000 (1.05-1.65 μm) VHR: R=25,000 (around He I+Paβ and Paγ)	R=5 (2 channels)	None	R = 20 R = 400 R = 2000*
Polarization split	YES (optional)	NO	-	YES*
Off-axis mode	YES*	-	-	-
Inner Working Angle @3.75 um	-	-	-	2 mas (AT), 3 mas (UT)
Diameter of the field of view	155 mas (AT), 34 mas (UT) @1.35 μm	222 mas (AT), 49 mas (UT) @ 1.94 μm	183 mas (AT), 41 mas (UT) @ 1.6 μm	430 mas (AT), 94 mas (UT) @3.75 μm
Interferometric observable	V^2, closure phase, differential phases	V^2, closure phase	-	Null depth, differential null depth
Magnitude limit	Limited by Baldr	K=11.5 (ATs) or 13.5 (UTs)	H=9.6 (ATs) or 12.9 (UTs)	L'=11 (ATs) or 13 (UTs)

* Contingent to additional funding.

Table 2. Preliminary performance of the VLTI Asgard modules

Feature	BIFROST	HEIMDALLR	Baldr	Hi-5
Precision on V^2	3% (LR arm)	5%	-	-
Precision on closure phase	0.5° (LR arm)	1°	-	-
Precision on differential phase	0.1° (HR arm)	-	-	-
Residuals piston RMS (nm)	-	< 100 (UT) < 50 (AT)	-	-
Injection stabilisation (in Strehl, in J band)	-	-	$> 50\%$ (AT)	-
RMS of injection (in Strehl, in J band)	-	-	$< 10\%$ (AT)	-
Precision on null depth (L=4 & R=18)	-	-	-	5×10^{-5} (UT) 3×10^{-4} (AT)

4. INSTRUMENTAL OVERVIEW

4.1 Instrumental setup and components

Asgard is a suite of four instruments that will be located on the Visitor 2 table (ex-AMBER's table). It will cover the light spectrum from Y to L bands (1 to 4 microns). The conceptual layout of ASGARD is given in Figure 1. The four 18-mm beams from the VLTI (bottom right) are first reflected on the beam compressors, which reduce the beam size to 12 mm, and then on the deformable mirrors.The L band light is then sent to Hi-5 with a dichroic while the Y-K band light is sent to the other modules (see module names). More information on the sub-systems of each module is given in the main text.

Asgard has two common modules for all the instrument modules. The first one is the Asgard Calibration and Alignment Unit (ACAU) that contains the sources for the spectral calibration of the modules and a 4-beam coherent light for internal alignment and cophasing. It also provided pickoffs that are flippable mirrors to pick the light from ACAU instead of the VLTI.

The second common module is the Asgard Common Optics (ACO) that has the following subsystems:

- Shutters (ASG-SHUT) to shut down all the instruments at once and beam per beam;
- Beam compressors (ASG-BC): consist of 4 pairs of optics to reduce the beams' size from 18 mm to 12 mm;
- Deformable mirrors (ASG-DM): comprise 4 deformable mirrors (DM) actuated by MEMS technology. They perform fringe tracking and injection control as well as the correction of higher aberration modes to maximise the injections in BIFROST and Hi-5;
- Dichroic (ASG-DIC): transmitting the L band to Hi-5 and reflecting the shorter wavelengths to the other modules.

HEIMDALLR has the following sub-systems:

- Longitudinal dispersion compensator (HEI-LDC): Each beam contains an LDC that is mounted on a piezo-electric linear stage;
- Dichroic and periscope (HEI-DIPER): the dichroic separates the Y-J-H and K bands. The periscope sends the Y-J-H band to Baldr/BIF-INJ at the upper level. The K band is transmitted toward HEIMDALLR's optics;

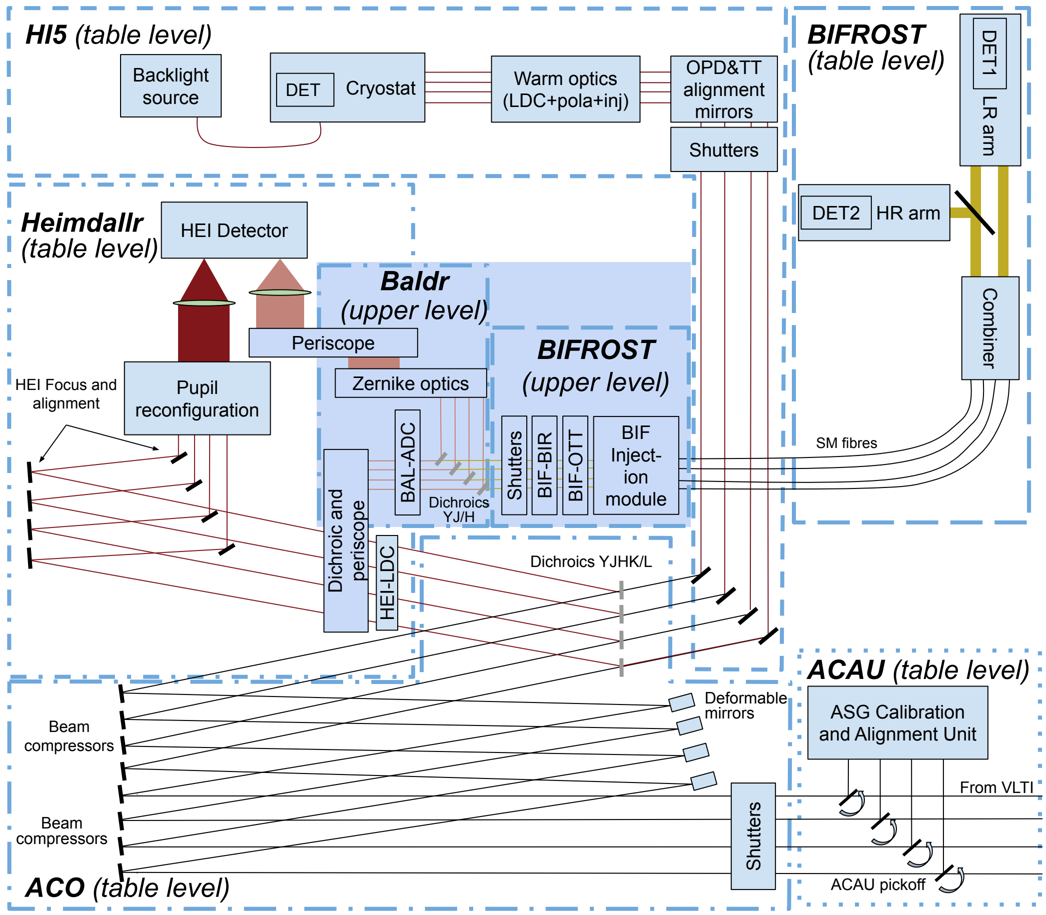

Figure 1. Conceptual layout of Asgard.This diagram is not to scale and the disposition of the modules is subjected to change but the order of the optical components should remain.

- Focus and alignment mirrors (HEI-FA): comprise 4 pairs of mirrors. They align and cophase HEIMDALLR. The mirrors are moved by stepper motor actuators;
- Pupil reconfiguration (HEI-COMB): comprising knife-edge mirrors to reconfigure the beams into a two-dimensional pattern. The K band-beams are reconfigured according to a 2-dimensional pattern providing 6 non-redundant baselines. The fringe pattern is used to perform wavefront sensing and science;
- Camera (HEI-DET): comprises the cooling system, its electronics and the detector. It collects and records the fringe pattern of HEIMDALLR and the signal from Baldr.

Baldr's sub-systems are:

- Atmospheric Dispersion Compensation (BAL-ADC): comprises 4 pairs of prisms. These devices will compensate for the chromatic dispersion effect between the Y and H bands, which degrades the injection efficiency and induces differential phases. They are actuated by a stepper-motorised rotary stage;
- Beam splitters (BAL-DIC): reflecting the H-band to Baldr and transmitting the J-Y band to BIFROST. An alternative beam splitter can instead be translated into place that reflects the J band to Baldr and transmits the H band to BIFROST;
- Zernike optics (BAL-PHA): is the phase sensor per se. It will either be a wavefront sensor and comprise phase masks and shutters to decompose the wavefront on a Zernike aberration base, or photonic lanterns which outputs code the incoming phases to replace the phase mask;

- Periscope (BAL-PER): sends the signals from BAL-ZER to the HEIMDALLR's camera.

BIFROST's sub-systems are:

- Shutters (BIF-SHUT): comprises four shutters. They can individually close each beam or all of them to perform the calibration tasks or protect the detectors for strong light while BIFROST is not operating;
- Birefringence correction (BIF-BIR): comprises LiNbO3 plates that compensate for the birefringence of the beam trains and the guided optics. The LiNbO3 plates are set on stepper-motorised rotary stages and are adjusted to maximise contrast on BIFROST;
- OPD & TT alignment mirrors (BIF-OTT): to cophase the input beams between BIFROST and HEIMDALLR and to optimise the light injection into BIF-INJ. A Differential Delay Line mirror mounted on a linear stage is used to cophase BIFROST with Asgard. A Tip-Tilt fast steering Mirror is used to actively optimise the coupling into the optical fibres;
- Injection module (BIF-INJ): comprises off-axis paraboloids (OAPs) and the fibre tips. The fibre tips receive the light to transport it to the core of BIFROST through single-mode fibres. The fibre tips are fixed at the focus of the OAPs;
- Combiner (BIF-COMB): comprises the combiner and a 90/10 beam splitter that can be moved in to record data simultaneously with BIFROST's LR arm and HR arm. The combiner makes the four beams interfere and creates 4 photometric outputs. A beam splitter separates the light meant for photometric monitoring and injects it back into the LR arm with a knife-edge mirror;
- LR arm (BIF-LR): comprises imaging optics, a prism for low-spectral dispersion at a fixed spectral resolution (R=50 to 80, precise value TBD) and a camera. Also, it contains a Wollaston on a translation that can be moved in to measure separate polarisation states and to improve the visibility calibration. The LR arm measures OPD drift, dispersion and fringe jumps to feed a feedback loop on the LDC and the BIFROST DLLs. The camera is a C-RED1;
- LR arm detector (BIF-DET1): comprises the detector, its electronics and cooling system. It collects the lowly-dispersed fringe pattern and the dispersed photometric channels;
- HR arm (BIF-HR): comprises imaging optics, a filter wheel with grisms for high spectral dispersion of the fringe pattern and a camera. It is used for measuring wavelength-differential quantities and closure phases;
- HR arm detector (BIF-DET2): comprises the detector, its electronics and cooling system. It collects the highly-dispersed fringe pattern. The camera is a C-RED1.

Hi-5's sub-systems are:

- Beam conditioner (HI5-SHUT): comprises shutters and diaphragms. It shuts the beams individually for calibration purposes and equalises the beam intensities to optimise the null depth;
- OPD & TT alignment mirrors (HI5-OTT): to cophase the input beams between Hi-5 and Asgard and to optimise the light injection into the photonic chip. They are actuated by stepper motors from Thorlabs;
- Warm optics (HI5-WO): comprises LDCs, polarisation control optics, the slicer and alignment camera. The LDC compensates for the chromatic phase across the L band and the water vapour effects via a feedback loop. The polarisation control compensates for polarisation effects which reduce the instrumental null depth. The slicer overlaps the four telescope pupils on the cold stop at the entrance of the cryostat. The alignment camera is an Infratec ImageIR 5300;

- Cryostat (HI5-CRYO): comprises a window, a cold stop, the photonic chip which combines the beams and creates photometric outputs, a wheel and imaging optics, the camera, the cryocooler and the vacuum system. The wheel contains grisms for different spectral resolutions and a folding mirror allowing back-injection. The chip is mounted on a 3-axe mount for alignment and focusing with HI5-WO. The cryocooler is the PT805 from Absolut system and the vacuum pump is the HiCube 30 Eco from Pfeiffer vacuum;
- Camera (HI5-DET): comprises the detector and its electronics. It collects the spectrally-dispersed signal delivered by the photonic chip. It consists of Teledyne's 5-micron Hawaii-2RG with SIDECAR cold electronics and Astroblank MACIE warm electronics;
- Backlight source (HI5-BACK): Fibered light source used to align Hi-5 with Asgard.

4.2 Control architecture

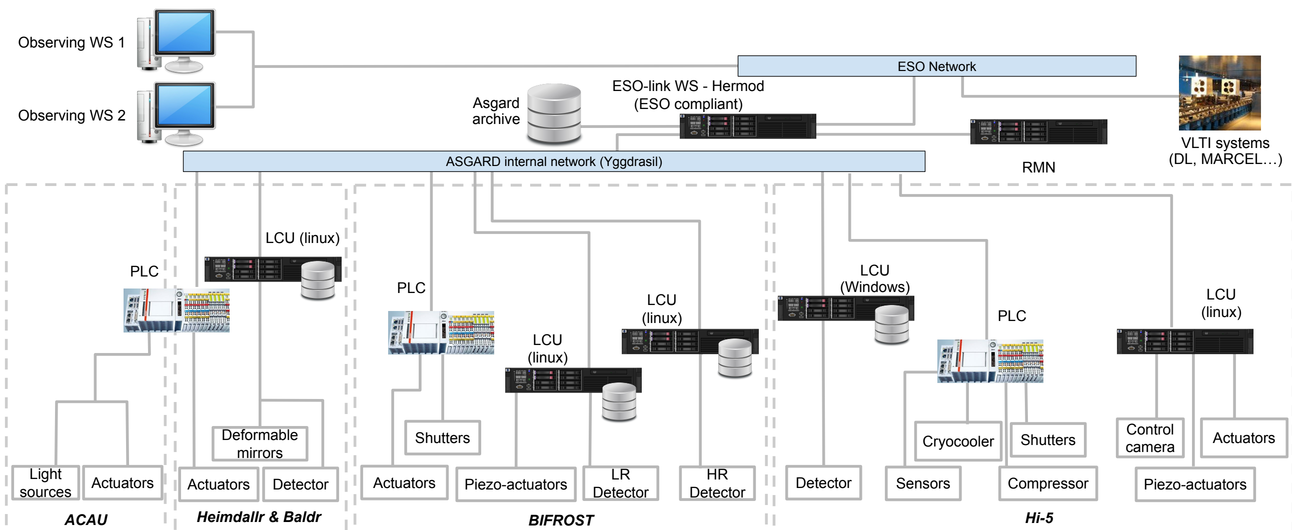

Figure 2. Preliminary Control architecture of Asgard.

The overall Asgard control architecture is given in Figure 2. The hardware architecture is designed so that two Observing Working Stations (WS hereafter) can operate all the modules. This centralisation allows the observer to run all the instruments simultaneously and to communicate with the VLTI systems. These WS can connect to Asgard through the ESO network while not necessarily being ESO compliant.

Asgard IT hardware and software are non-ESO compliant, hence must be kept separate. However, Asgard modules need to interact with ESO systems such as the RMN, the delay lines and the calibration sources. The suggested solution is to create a local network on which the IT components of each module are connected: the *Asgard Internal Network* called *Yggdrasil**. An *ESO-link WS*, called *Hermod*†, connected to *Yggdrasil*, will interact with ESO systems, the RMN and transmit data to and from Asgard's module that require such data. *Hermod* will respects ESO's standards for hardware and software. From the ESO network point of view, Asgard is a unique computer represented by *Hermod*.

Each module has one or two Local Control Units (LCU) or Programmable Logic Controllers (PLC) to drive Asgard's sub-systems and components monitor cameras, science detectors and the piezo-actuators). The LCUs are connected to the Asgard Internal Network and are driven from the *Observing WS*. The PLCs directly control the opto-mechanical components and are controlled by the *Observing WS* similarly to the LCUs.

Each module (except ACAU) has its own data storage embedded in its respective LCU. Consistent with the requirement for VLTI VIs to keep their data flow separate from the ESO, Asgard also has a general archive,

*Sacred tree which supports all the worlds in the Nordic mythology
†Messenger of the gods in the Nordic mythology

the Asgard Archive. It has sufficient capacity to store Asgard data acquired over several weeks. In a future extension, the Asgard archive could also serve as the hub for feeding Asgard data into the ESO archive.

The LCUs managing the detectors have direct access to it to write the frames and the user can access the storage via the *Observing WS*. The connections between the WS and LCUs are made with Ethernet cables and the TTL protocol.

The Instrument Software Package will be subdivided into the following software modules:

- The ICS (Instrument Control Software): to control all devices connected to the LCU on which it is installed, except the detector. There will be one ICS per module.
- The DCS (Detector Control Software): to control the detector. There will be one DCS per LCU connected to a detector.
- The OS (Observing Software): to coordinate the acquisitions of the instrument, interfaces with the E O-link WS, with the storages of the modules and the Asgard archive.
- The LS (Link Software): exchanges information and instructions between ESO and Asgard networks.

4.3 Data flow

The data flow is shown in Figure 3. Asgard will use its own observing blocks. After each observing night, the data (under FITS format) and the observing logs are copied to the local Asgard database. The data and the logs are copied to different places depending on the instrument (BIFROST data sent to the University of Exeter, HEIMDALLR/Baldr sent to ANU and Hi-5 data sent to KUL). The transfer would be done by physically moving the storage drives. The data are reduced and quality controls check the quality of the final data. Reduced data are formatted in OIFITS file in order to be published and put on the JMMC OiDB with their observing logs.

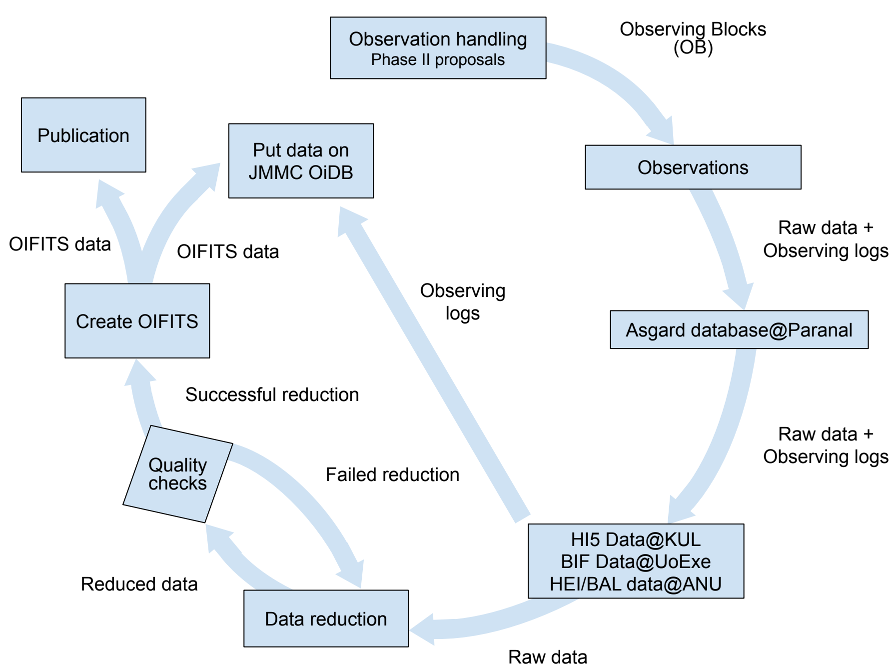

Figure 3. Preliminary data flow plan of Asgard.

5. CONCLUSION

Asgard, new instrument suites proposed to ESO (P110, March 2022) to open new unique capabilities at the VLTI (YJH high-spectral resolution and L-band high-contrast nulling interferometry) and to enable exoplanet imaging at milli-arcsecond angular separation. It consists of 4 different modules: BIFROST (YJH high-spectral resolution (R=50, 1000, 5000, 25000)), BALDR (Zernike Wavefront Sensor in H band), HEIMDALLR (high-sensitivity fringe tracker (dual K band)), and Hi-5 (L-band (3.5-4 microns) nulling interferometer based on a photonic chip and self-calibration data reduction techniques). The suite is currently in the design and preparation phases. The design aims at making the instrument interoperable and making its data integrated to the existing data flows.

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