GENIESIM: THE GENIE SIMULATION SOFTWARE

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ABSTRACT

GENIEsim, the GENIE simulation software, is an IDL-based code to simulate future observations with the Ground-based European Nulling Interferometer Experiment, which should be commissioned on the Very Large Telescope Interferometer (VLTI) in 2007. The code simulates operation in the mid-infrared (L' and N bands) and includes all major noise sources. The atmospheric turbulence is described by a Kolmogorov power spectrum, from which random time series are computed for perturbations to the optical paths. The effect of turbulence is reduced by means of control loops, which are either included in the VLTI facility (MACAO, PRIMA) or specific to the GENIE instrument. The output of GENIEsim is a time series of fluxes computed by integration of a source field multiplied by the GENIE transmission map, projected onto the plane of the sky. Simulations have already allowed to identify critical points in the design of the instrument, such as OPD and dispersion control, calibration of stellar leakage and background subtraction.

Key words: Nulling interferometry: GENIE; simulation: observations, atmospheric turbulence, thermal background.

1. INTRODUCTION

Within the frame of the Darwin programme, the European Space Agency (ESA) and the European Southern Observatory (ESO) intend to build a ground-based technology demonstrator for nulling interferometry. This ground-based demonstrator built around the VLTI will combine all optical functions foreseen into the future Darwin Infrared Space Interferometer. It will benefit from the existing VLTI infrastructure, including the telescopes with chopping and adaptive optics, the delay lines, the fringe sensors and the beam-combining laboratory. The overall performance of the instrument will heavily depend on the performance of all VLTI subsystems and in particular on the adaptive optics and co-phasing subsystems. The GENIE optical bench within the VLTI laboratory will provide the functions specific to the nulling interferometry technique, namely OPD and dispersion control, photometry and amplitude control, polarization matching, spatial filtering, phase shifting, beam combination, spectrometry, detection, electronics, and operation at cryogenic temperatures.

In the design of such a complex instrument, early access to simulation software is a valuable asset. For example, the choice of the operation wavelength and the design of the control sub-systems are two critical points that cannot be addressed without a realistic simulation of the instrument operation. Therefore, we are currently building an IDL package called GENIEsim to simulate future observations with the GENIE instrument, taking into account all noise sources encountered in ground-based interferometry. The simulator is based on the physical modeling of atmospheric turbulence and on experimental data when available, e.g. for the sky background fluctuations and for the sky transmission.

This paper presents the architecture of GENIEsim, beginning with the specification of the astronomical sources and ending up with a time series for the output flux in photo-electrons per second. Special emphasis is put on the physical modeling of the noise sources and of the control loops, which are the critical parts of the simulation. The default aperture configuration is a single Bracewell interferometer based on two VLT Unit Telescopes, but any other configuration can be implemented in GENIEsim, including the Degenerate Angel Cross and the double Bracewell configurations (Gondoin et al., 2003).

2. THE ASTRONOMICAL SOURCES

The simplest targets for the GENIE instrument are single stars, which will be used to perform nulling tests with the highest and most stable nulling ratio.

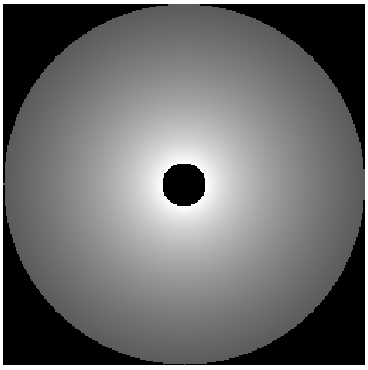

Figure 1. Image of a flat circumstellar dust disk produced by DISKPIC, within the field-of-view of a VLT Unit Telescope (345 milli-arcsec in radius in the N band). The inner and outer radii were set to 0.5 and 7 AU respectively, while the field-of-view radius corresponds to only 3.45 AU at a distance of 10 pc.

Besides these technology tests, GENIE will mainly survey nearby main-sequence stars for the presence of circumstellar disks. Additional targets for GENIE are low-mass companions, including binary stars, brown dwarfs and even hot extrasolar giant planets ("hot Jupiters"), orbiting close to their stars.

2.1. Stars and planets

Presently, planets and stars are assumed to be black bodies in thermal equilibrium. A planet is thus defined only by its radius and orbital elements. Realistic planetary and stellar models are still to be implemented.

2.2. Circumstellar disks

Two packages are used inside GENIEsim to produce images of circumstellar dust disks projected on the plane of the sky.

1. The DISKPIC package produces images of geometrically and optically thin circumstellar disks. In this package, the dust properties are assumed to be independent of vertical position in the disk (valid for thin disks) and independent of azimuth (valid for symmetric disks). The disk is characterized by its density and temperature power-laws. Only the thermal emission is considered, assuming that the grains emit as blackbodies. This disk model is particularly appropriate for debris disks, but not for circumstellar disks around Young Stellar Objects (YSO) which are optically thick. However, DISKPIC can still simulate flared YSO disks when seen face-on, with a user-specified Spectral Energy Distribution (SED).

2. ZODIPIC is an IDL package developed by Marc Kuchner. It is built on a model for the solar system observations made by the DIRBE experiment aboard the COBE satellite. It can compute images at scattering as well as thermal wavelengths, and offers a variety of tweakable parameters accessible from the IDL command line. ZODIPIC is available online at http://cfa-www.harvard.edu/~mkuchner/.

2.3. Thermal background

For infrared observations, an important source of photons is the thermal emission from the atmosphere and from the instrument itself. The sky emission is modeled by a grey body at a temperature of 284 K with a wavelength-dependent emissivity which is the complement of the sky transmission. Its spectrum is plotted in Figure 2. The instrumental background produced by the optical train of the VLTI is modeled by a blackbody at 288 K. Even if the theoretical emissivity of the VLTI is about 60% in the mid-infrared, an emissivity close to 100% is expected due to the imperfections of the relay optics. Comparison of the two contributions in Table 1 shows that the instrumental background is dominant in the case of the VLTI.

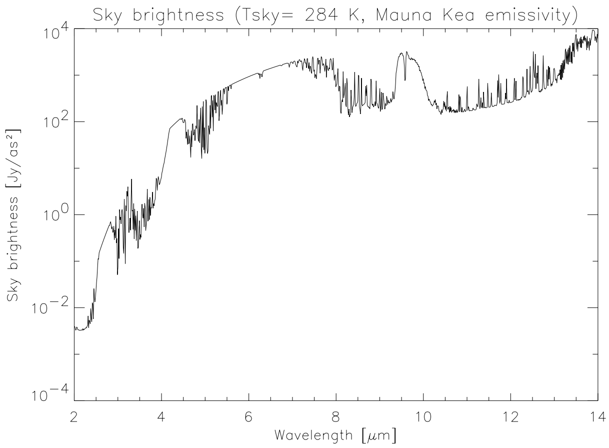

Figure 2. Model for the IR sky brightness, based on measurements at Mauna Kea, and extrapolated to the Paranal atmospheric conditions.

Table 1. Infrared brightness of the sky at the telescope entrance and of the VLTI optical train at the entrance of GENIE, computed at the central wavelength of the infrared atmospheric windows. The total background is given in number of photons per second at the entrance of GENIE.

	K	L'	N
Sky brightness (Jy/as^2)	0.004	4.2	599
VLTI brightness (Jy/as^2)	0.012	33.2	6985
Total brightness (ph/s)	1.5e4	1.0e8	4.8e8

3. NOISES AND ATMOSPHERIC EFFECTS

3.1. Shot noise

Shot noise is always a major contributor to the total noise for mid-infrared observations because of the huge incoherent background emission. The equivalent background flux in the interferometric field-of-view of a Unit Telescope is respectively of 1 Jy and 1700 Jy in the L' and N bands. The stellar flux is typically of a few Jy, but it is reduced by a factor of 1000 or more by the nulling process. Therefore, thermal background is always the dominant source of shot noise.

3.2. Stellar transmission noise

Due to the finite extent of the stellar disk, a fraction of the starlight leaks through the central dark fringe of the transmission map. In addition to this "physical" stellar leakage, a random "instrumental" leakage will be produced by atmospheric turbulence and by the imperfections of GENIE, which translate into three types of errors:

- *phase*: The fluctuations in the column density of dry air and water vapor produce random variations of OPD, with Power Spectral Density (PSD) following the usual Kolmogorov law. Moreover, the wavelength-dependence of the refraction index of water vapor produces longitudinal dispersion, a non-linear variation of the OPD error as a function of wavelength (Meisner and Le Poole, 2003).
- *intensity*: Intensity mismatches are mainly due to fluctuations of the Strehl ratio delivered by the MACAO adaptive optics, and to the residual tip-tilt. Based on performance simulations for MACAO, the intensity coupled into the spatial filters is computed.
- *polarization*: We currently assume that this source of stellar leakage can be made negligible by fine tuning of the instrument during the commissioning.

Taking into account the random fluctuations of phase and intensity, we end up with a residual stellar signal highly variable with time. A typical time series for the stellar transmission is given in Figure 3. In this figure, the atmospheric effects have been reduced by means of control loops (see section 4).

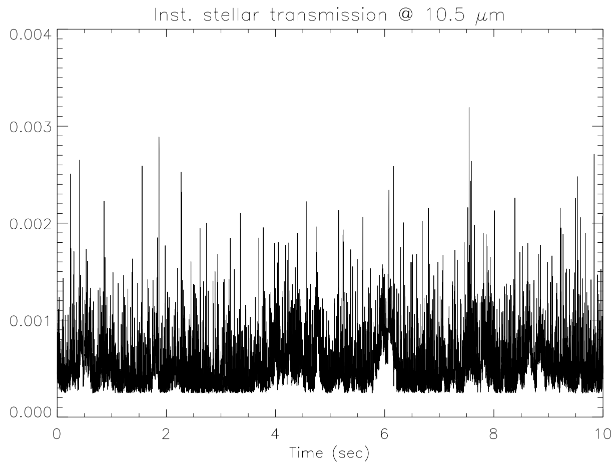

Figure 3. Instantaneous stellar transmission for a UT2-UT3 configuration observing a Sun-like star at 10 pc in the N band. The fluctuations have been reduced by means of control subsystems.

3.3. Background fluctuation noise

The two background components must be considered separately when it comes to fluctuations:

- *sky*: According to Käufl et al. (1991), the infrared sky noise power spectrum in the N band is proportional to $1/f$ at low frequencies, and reaches the level of the shot noise power spectrum at a frequency of 5 Hz. Such a PSD has been implemented in GENIEsim and is used to produce time series for the background fluctuations.
- *VLTI*: A good model of the VLTI thermal emission cannot be built without measurements. A testing campaign is currently undertaken with the MIDI interferometer to characterize the background fluctuations produced by the VLTI, as well as by the Paranal atmosphere. The fluctuations of the instrumental background will be implemented in GENIEsim as soon as the data are available.

3.4. Detector noise

Detector noise is taken into account in GENIEsim assuming state-of-the-art infrared detectors, optimized for high background operation.

4. CONTROL LOOPS: COMPENSATION OF ATMOSPHERIC EFFECTS

Without the OPD and intensity corrections by the control loops, atmospheric effects such as piston, longitudinal dispersion or wave front distortion would make long exposure impossible for ground-based nulling interferometry. For example, the OPD fluctuations produced by atmospheric turbulence have a typical amplitude of 20 μm. If not corrected, they would shift the fringe pattern so much that the star would spend half of the observation time on a bright fringe!

The VLTI facility provides two control systems, respectively for OPD and wave-front correction, as well as a chopping facility:

- The *Fringe Sensing Unit* (FINITO or PRIMA), together with the Delay Lines, allows to compensate OPD errors in the infrared H and/or K bands, with a typical residual error of 100 nm RMS for a bright guide star.
- The *Adaptive Optics System* (MACAO or STRAP) provide, for MACAO on the Unit Telescopes, a typical Strehl ratio of 64% in the K band with an RMS fluctuation of 7%. For the Auxiliary Telescopes, STRAP will only correct the tip-tilt error.
- A *chopping mirror* is available on the UT's and the AT's to alternate between target and a nearby sky region for background subtraction at a maximum frequency of 5 Hz.

The VLTI control systems are well designed for classical interferometry (with MIDI and AMBER), but do not reach the performances needed for GENIE as shown by Wilhelm and Gitton (2003). Additional control systems are thus planned within GENIE (see illustration in Figure 4):

- A K/L band Fringe Sensing Unit, which will also measure the longitudinal dispersion,
- A fast Delay Line (up to a few kHz) to reduce the residual OPD,
- An N-band dispersion sensing unit if the K/L band FSU does not yield a sufficient precision on the dispersion measurement,
- Two pairs of movable ZnSe wedges to correct for the longitudinal dispersion,
- Two intensity sensors and associated intensity matching devices to measure and correct the intensity actually injected in the two spatial filters,
- A possible internal chopping device if the 5 Hz chopping is not sufficient. Internal chopping could be implemented either with phase modulation, e.g. between two Bracewell interferometers (Gondoin et al., 2003), or by placing additional fibers in the focal plane to sample the background emission around the science fiber.

All these control systems are modeled in GENIEsim, with the possibility to specify any realistic design for the systems, and the choice to switch them off.

5. ARCHITECTURE, OPERATION AND OUTPUT OF GENIESIM

Lacking a fancy GUI, the operation of GENIEsim is currently based on a single ASCII file where all simulation parameters are listed:

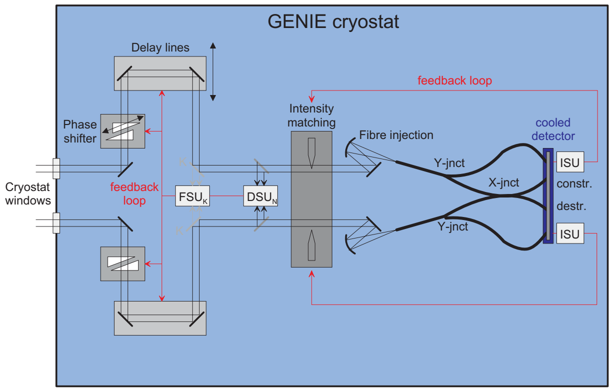

Figure 4. A possible design for the GENIE instrument. This scheme illustrates the operation of additional sensing units (SU) and correction systems for OPD, dispersion and intensity control that could be implemented within GENIE itself. Fiber optics have been used for the clarity of the sketch. It is not proven yet that such fiber-based beam-combiners will be available in the mid-infrared at the time GENIE comes online.

- observation parameters (date, time, ...),
- configuration (telescopes),
- chopping (external/internal, frequency, ...),
- photon parameters (wavelength, ...),
- atmospheric conditions,
- VLTI parameters (throughput, emissivity, pointing errors, ...),
- characteristics of detectors (including the detectors for the sensing units),
- description of the sources.

For each Observation Block (of 100 sec), the simulator generates time sequences for the random variables, based on the input power spectral densities and on the transfer functions of the control loops. Control loops are self-calibrated to minimize their residual error. Taking into account all random errors, the fringe pattern is computed each millisecond, and the flux transmitted by GENIE is deduced by integration of all field sources on the transmission map. The output of GENIEsim is a time series of the fluxes recorded at each detector read-out (see Figure 5).

6. PERFORMANCE SIMULATION OF GENIE

Simulated observations of various targets are presented in three accompanying papers:

- Simulations of Vega-type stars by Absil et al. (2003) have shown that disk parameters such

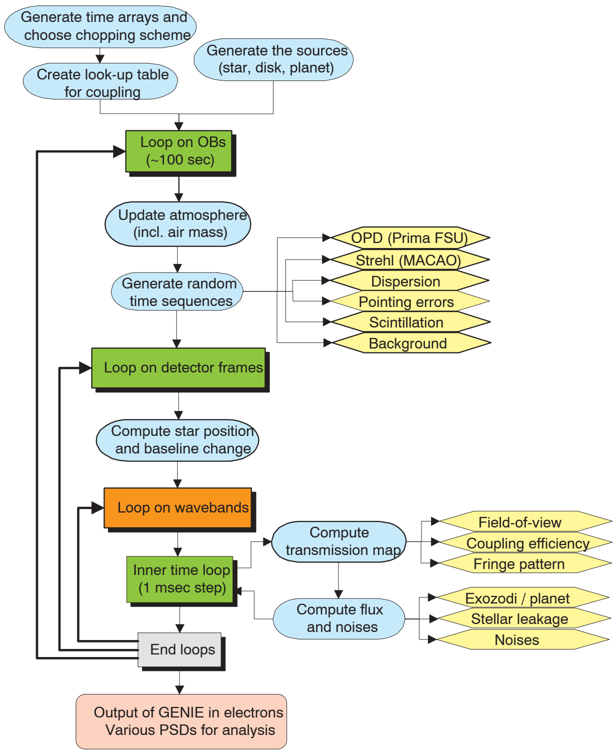

Figure 5. Architecture of the GENIEsim software.

as luminosity, inner radius or density power-law could be retrieved with a relative accuracy of 1% or better within an hour of integration. This paper also shows that, for nearby Sun-like stars, GENIE should be able to detect zodiacal disks as faint as 25 times our local zodiacal cloud.

- As shown by Kaltenegger et al. (2003), GENIE will provide a new insight on the inner dust and on the physics of disks around Young Stellar Objects with an unprecedented accuracy.

- According to den Hartog et al. (2003), low resolution spectra could be obtained on a few hot Jupiters. The simulations presented in this paper show that GENIE, in a L'-band single Bracewell configuration, could detect the hot Jupiter around τ Bootis in a few hours time with a signal-to-noise ratio of about 80.

These simulations demonstrate that GENIEsim is a powerful tool to estimate the future performances of the GENIE instrument as a function of the chosen design and of the control sub-systems. GENIEsim will thus help identify the critical points in the design of the instrument and the needs of future users.

7. VALIDATION OF GENIESIM

How can we be sure that GENIEsim correctly models what GENIE is going to do? This is an equally tough as important question. There are several answers:

- We thoroughly check the functioning of each individual module and compare its outputs with the specifications – a basic requirement in software design.

- We use as much as possible real data instead of models, e.g. for the PSD of the atmospheric and instrumental background, or the delay line noise in the control loops. In this way we reduce the problem of stacking wrong hypothesis upon wrong hypothesis. The difficulty with this approach is that good data is scarce, in particular in the high-frequency domain.

- ESO is currently developing a ray-tracing model for the VLTI-GENIE interface. Detailed cross-checking between this model and GENIEsim will provide a valuable check on the computational correctness of GENIEsim.

- The proof of the pudding will of course be a comparison between GENIEsim output and a data set obtained with a real interferometer, preferably an earlier model than GENIE. Given the flexibility of the GENIEsim software, it is able to simulate existing interferometers, such as AMBER or MIDI.

8. CONCLUSIONS

The GENIEsim simulation software is presently mature enough to provide realistic models of nulling interferometric observations with GENIE. The validation of the software is an ongoing process. The use of GENIEsim has already been demonstrated in the identification of critical design issues, such as the choice of the wavelength band and control loop performance specifications, and the definition of observational strategies for the various targets.

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