Title: **Summary Report**

Contract: ESTEC/Contract no. 15542/01/NL/HB (incl. CCN-1 and CCN-2)

DARWIN FINCH System Simulator

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Table of Contents

1 Scientific and Programmatic Background

FINCH, the DARWIN system simulator for **F**ast **IN**terferometer **CH**aracterisation, is a software simulator for precise quantification of the end-to-end science performance of the DARWIN **I**nfra**R**ed **S**pace **I**nterferometer mission. For a given celestial observation scene and a predefined observation strategy FINCH shall calculate the resulting timelines of the science detector outputs.

DARWIN is one of the most challenging space missions ever considered by the European Space Agency (ESA). It aims at detecting Earth-like planets orbiting nearby parent stars and to characterise the planets' atmospheres in the search of traces of extra-terrestrial organic life. DARWIN uses an optical nulling interferometry technique which coherently combines the light beams collected by telescopes, each on-board of a free-flying independent spacecraft and all pointing precisely towards the same parent star. The coherent (destructive) combination of the light beams received by the telescopes shall sufficiently cancel the light emitted by the bright on-axis parent star in order not to mask the weak infrared signal originating from the planet(s) orbiting it. This interferometric nulling technique requires the stabilisation of the wavefronts and optical path lengths of the different star light beams up to the beam recombination optics down to small fractions of a wavelength, i.e., down to roughly one nanometer.

The enormous sensitivity of the DARWIN measurement principle against all sorts of imperfections and disturbances (mechanical, optical, thermal) requires for FINCH a flexible and extensible simulator concept apt to integrate models with differing levels of realism and of different degree of sophistication originating from various engineering disciplines.

In the assessment and definition phase of the DARWIN mission, FINCH is intended to provide reliable predictions of the science performance in order to support configuration trades mainly on optical instrument level. In future DARWIN phases FINCH shall be more and more refined, extended and used for detailed inter-disciplinary performance analyses. In this context it might be used in the future, for instance, for a quantification of the GNC performance based on a realistic optical model of the fringe sensor units or for the analysis of the science performance under micro-vibrations and thermal deformations. Finally, during the DARWIN in-orbit mission operations phase, FINCH might be applied for the routine analysis and definition of observation strategies for selected celestial targets in support of mission operations planning.

The principal objectives of the meanwhile accomplished study phases 1 and 2 of FINCH were concentrated on the establishment of a generic *opto-dynamic* simulator (called FINCH/OPT). These objectives were as follows:

- Generic opto-dynamic modelling of multi-aperture nulling interferometers
- Implementation of candidate interferometer configurations (simple Bracewell, Bow-Tie, X-Array, TTN+) with differing levels of detail.
- Validation of the established models in the instance of Astrium's nulling breadboard.
- Definition of the interface between FINCH/OPT and the guidance, navigation and control (GNC) related formation-flying part of FINCH (FINCH/GNC) to prepare the future integration of the two main constituents of FINCH developed under separate contracts.
- Establishment of a shared repository and of configuration control procedures for FINCH.

2 Project Organisation

EADS Astrium GmbH in Friedrichshafen has been awarded the prime-contractorship for the development of FINCH/OPT under ESTEC contract no. 15542/01/NL/HB based on an unsolicited study proposal.

Due to its intimate familiarity with the optics code BeamWarrior, Dr. Rainer Wihelm from the European Southern Observatory (ESO) in Garching has been subcontracted for extending the modelling capabilities of BeamWarrior, an advanced optics code for opto-dynamic systems developed jointly by Astrium GmbH and ESO. After Dr. Wilhelm's departure from ESO in 2004 his responsibilities have been taken over by Kevin Scales (ESO).

The initial FINCH/OPT contract for Phase 1 started in October 2001 and ended with the final presentation in December 2002 at ESTEC. The continuation of the work in Phase 2 was formalised by contract change notice CCN-1 and started beginning of June 2003. The Phase 2 final presentation took place in the beginning of June 2005 at ESTEC.

In parallel to the Phase 2 work a FINCH/OPT validation campaign has been performed under contract change notice CCN-2 in order to ensure the fidelity and representativity of the models developed.

The basic funding for the FINCH/OPT project was provided by ESTEC. Nevertheless substantial internal company funding has been invested by EADS Astrium GmbH in order to increase the depth and quality of the work performed.

3 FINCH Objectives and Technical Requirements

The principal objectives of the meanwhile accomplished study phases 1 and 2 of FINCH were concentrated on the establishment of a generic *opto-dynamic* simulator (called FINCH/OPT) and were as follows:

- Generic opto-dynamic modelling of multi-aperture nulling interferometers
  - with distributed optics spread over several spacecraft
  - for different interferometer configurations with different beam combination optics and modulation schemes
  - covering the optical chain end-to-end from the celestial target to the science detector outputs
  - covering the full DARWIN wavelength range and arbitrary celestial observation scenes
  - including the adequate representation of optical elements such as higher-order aspheres, beam splitters, single-mode fibers, coatings of optical surfaces, phase retarding elements (e.g. achromatic phase shifters), etc.
- Implementation of candidate interferometer configurations (simple Bracewell, Bow-Tie, X-Array, TTN+) with differing levels of detail.
- Validation of the established models in the instance of Astrium's MAII Nulling Breadboard.
- Definition of the interface between FINCH/OPT and the guidance, navigation and control (GNC) related formation-flying part of FINCH (FINCH/GNC) to prepare the future integration of the two main constituents of FINCH developed under separate contracts.
- Establishment of a shared repository and configuration control procedures for FINCH.
- Provision of consultancy and training for FINCH/OPT users.

The main technical requirement for the to-be-designed, to-be-modelled and to-be-analysed interferometer configurations was the suppression of the stellar leakage of the on-axis parent star. The allowable level of stellar leakage arriving at the science detector must not exceed the order of magnitude of 1 ppm of the power measured at detector level in case of a fully constructive interference of the light originating from the parent star.

4 Basic Concepts

The DARWIN system simulator FINCH consists of two parts: of the guidance-, navigation- and control-related formation-flying part (FINCH/GNC) developed by EADS Astrium SAS under ESTEC contract in the framework of the Interferometer Constellation Control study (ICC) and of the optical part (FINCH/OPT) representing the science chain from the celestial targets to the science detectors as well as the optical metrology systems required as sensors for formation-flying.

These two parts can both either be used stand-alone (cf. Figure 4-2 for the stand-alone FINCH/OPT simulator) or alternatively in combination (cf. Figure 4-1). In the latter case FINCH/GNC will be the master over FINCH/OPT. In case of stand-alone use of one of the two FINCH parts, the signals obtained otherwise from the complementary part of FINCH have to be generated by more or less simple substitute models.

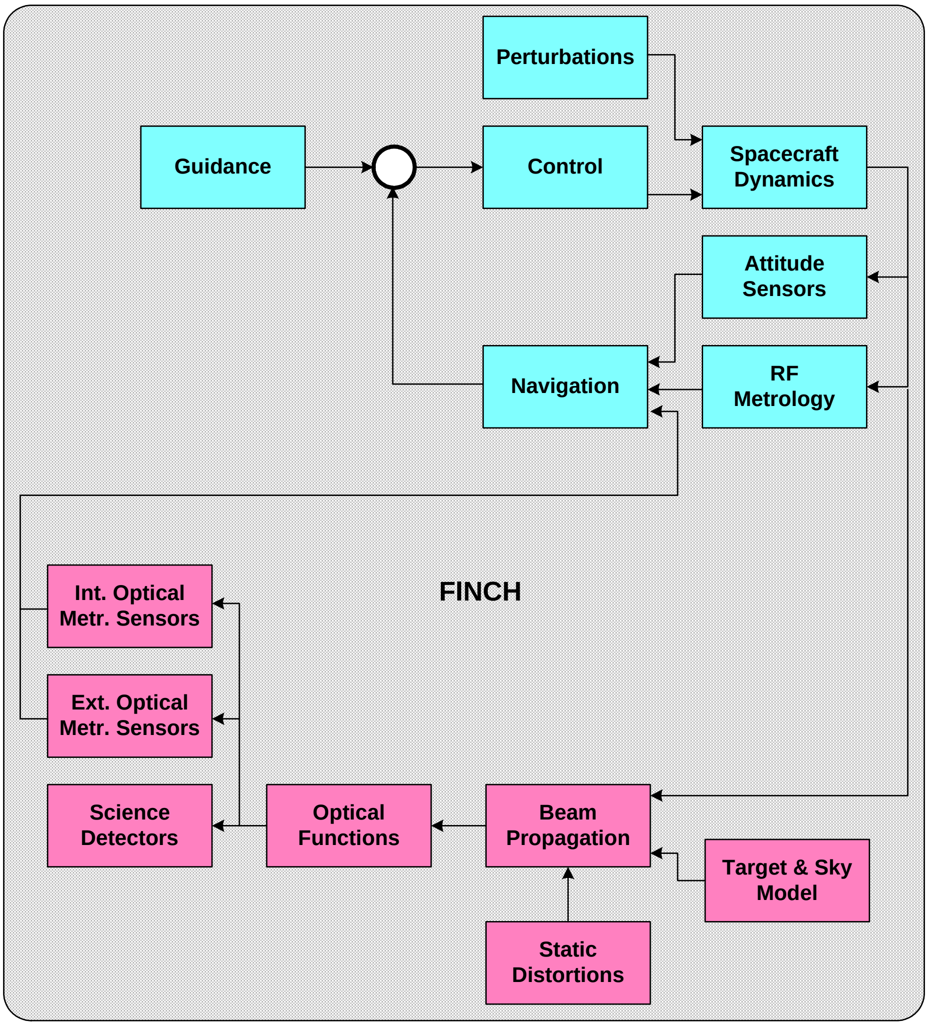

Figure 4-1: Integrated use of FINCH consisting of the GNC part FINCH/GNC (in blue) and of the optical part FINCH/OPT (in red).

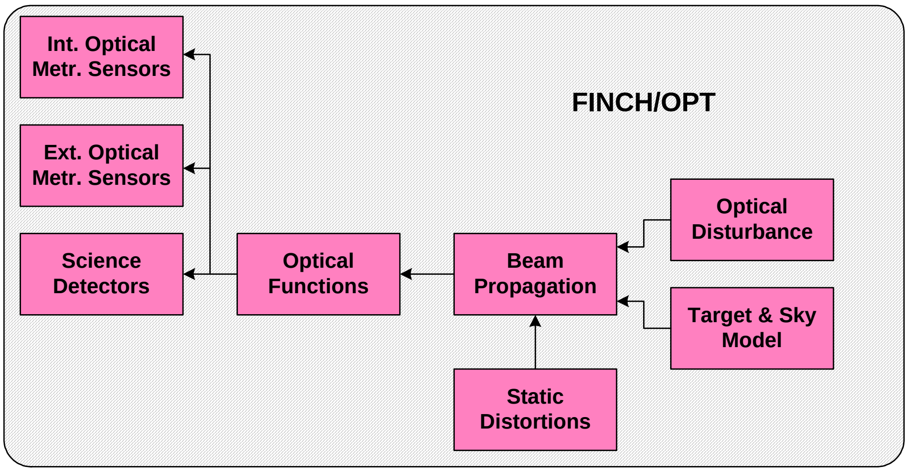

Figure 4-2: Stand-alone use of FINCH/OPT, the optical simulator forming part of FINCH

The object of the present study is mainly restricted to FINCH/OPT, the optical part of FINCH. The creation of any particular FINCH/OPT model is based on BeamWarrior, an advanced optics code developed over many years jointly by EADS Astrium GmbH and ESO. The typical development of an opto-dynamic FINCH/OPT model is based on BeamWarrior and is depicted in Figure 4-3.

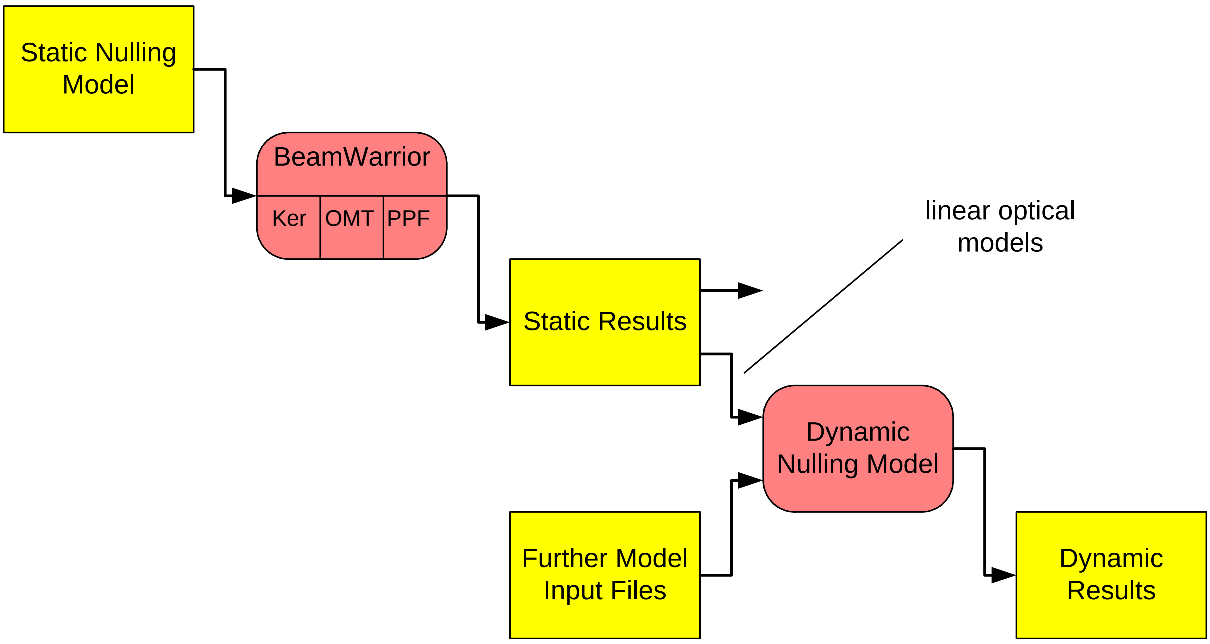

Figure 4-3: Development of an opto-dynamic FINCH/OPT model of a nulling interferometer concept. The (not shown) validation of the dynamic nulling model is based on the comparison of (static) results obtained from the BeamWarrior model with dynamic FINCH/OPT results.

The development of a FINCH/OPT model is basically a four-step process:

1. The first step is to create a static BeamWarrior model yielding static results varied owing to to user-defined perturbations of the geometry of the modelled optical set-up.
2. The second step is to generate linear optical substitute models (sensitivity matrices) with BeamWarrior that are computationally by orders of magnitude faster than the original BeamWarrior model.
3. In a third step these linear optical models are integrated into the dynamic simulation environment of Matlab/Simulink™ and combined with dedicated optical functions that are themselves mostly optimised derivatives of the BeamWarrior code.
4. In a final step the results obtained with the opto-dynamic model have to be compared with the results of the original static BeamWarrior model in order to ensure the validity of the substitute model

Only the first three steps of this process are visualised in Figure 4-3.

5 Phase 1 Achievements

The work performed during Phase 1 was focused on upgrading the functionality of BeamWarrior in order to enable this optical analysis program to adequately represent nulling interferometer concepts and their components as foreseen for DARWIN. BeamWarrior and its documentation had to be significantly upgraded for this task in particular with respect to the following functionalities:

- Representation of polychromatic polarised or unpolarised point sources
- Coherent superposition of electric fields due to pupil-plane or image-plane beam combination
- Modal filtering of beams by means of single-mode step-index fibers
- Representation of coated optical surfaces like e.g. beam splitting layers
- Generation of linear optical models
- Simulink S-functions for computation of electric fields, for modal filtering by means of single-mode step-index fibers and for coherent superposition of beams

Based on the new BeamWarrior functionalities a static model of a simple Bracewell nulling interferometer could be established. The optical set-up underlying this model is depicted in Figure 5-1. It comprises two free-flying telescopes and a central beam recombination unit. The optical design for the beam recombination unit is based on the Astrium nulling breadboard developed under another ESTEC contract. An intensity distribution on the fiber tip calculated with this BeamWarrior model is shown in Figure 5-2.

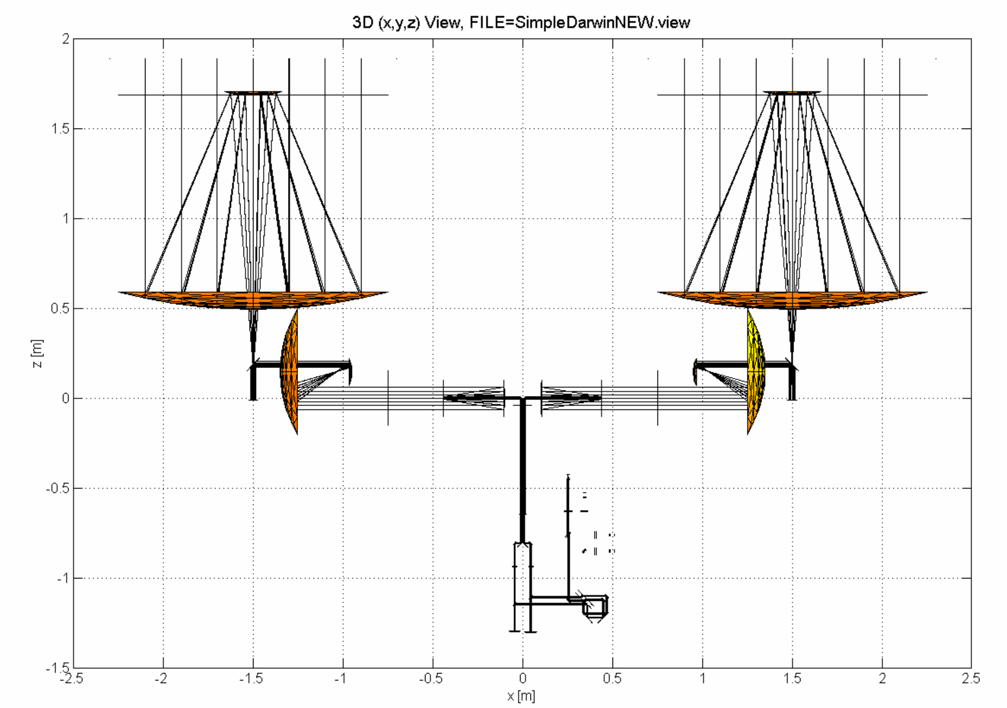

Figure 5-1: BeamWarrior optics view of a Bracewell nulling interferometer. The distance of the two telescopes from the central beam recombination unit as shown above is too small to be representative for DARWIN.

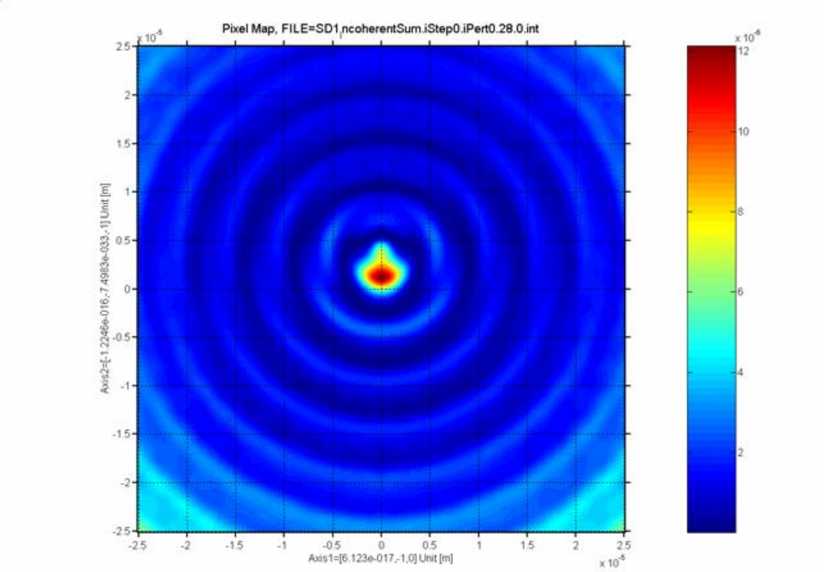

Figure 5-2: BeamWarrior intensity distribution on the entrance of the single-mode fibre used in the beam recombination unit of the Bracewell nulling interferometer for wavefront filtering. The spatial extension of the intensity map is 50×50 µm while the fiber core radius is 3 µm. The intensity distribution shows the effect of imperfect alignment.

After thorough testing, the BeamWarrior model was used to calculate linear optical models. Based on these models and optical functions (Simulink S-functions) for computation of electric fields, for modal filtering by means of single-mode step-index fibers and for coherent superposition of beams, a first opto-dynamic FINCH/OPT model for a nulling interferometer could be set up.

In addition to coding and model building activities, maintenance and configuration control procedures have been established for FINCH. Problems detected in the software are customarily reported to Astrium and if need be corrective action is initiated and its success checked.

Moreover, a three-day training session for members of the DARWIN community has been held at Astrium's premises.

6 FINCH Validation (CCN-2)

A validation campaign has been undertaken in order to check the validity of the results calculated by means of BeamWarrior and FINCH/OPT. The in-house availability of the Astrium nulling breadboard offered the opportunity to perform measurements on a hardware realisation of a nulling interferometer and to compare these measurements with BeamWarrior and FINCH simulation results.

Initially, this comparison yielded significant differences and it took a considerable amount of time to recognise their causes. The main cause discovered was related to the discretisation used for parametrising Jones surfaces in BeamWarrior. Jones surfaces are used to represent (coated) surfaces in terms of their reflectance and transmittance properties as a function of incidence angle and wavelength. The then too coarse discretisation of the incidence angle in the (.ac) data files used to parametrise such Jones surfaces was found to significantly deteriorate the null depth achievable in simulation. Only after tedious correction of these data files a null depth below 1.e-6 as obtained on the breadboard could be reproduced in the simulation.

Apart from the validation activities proper, a lot of insight could be gained in the course of this activity. It could be studied, for instance, to which extent beam misalignments and intensity mismatches impair the achievable nulling performance.

The comparison performed between BeamWarrior and FINCH results yielded very good agreement.

Furthermore the open-loop OPD fluctuations on the Astrium nulling breadboard due to air turbulences have been measured and approximated in the FINCH model by normally distributed band-limited coloured noise. A simple closed-loop OPD control has been implemented based on the same measurement signals as in the nulling breadboard. The closed-loop OPD adjustment has been effectuated as in the nulling breadboard by means of an optical delay-line. The achieved nulling performance is shown in Figure 6-1.

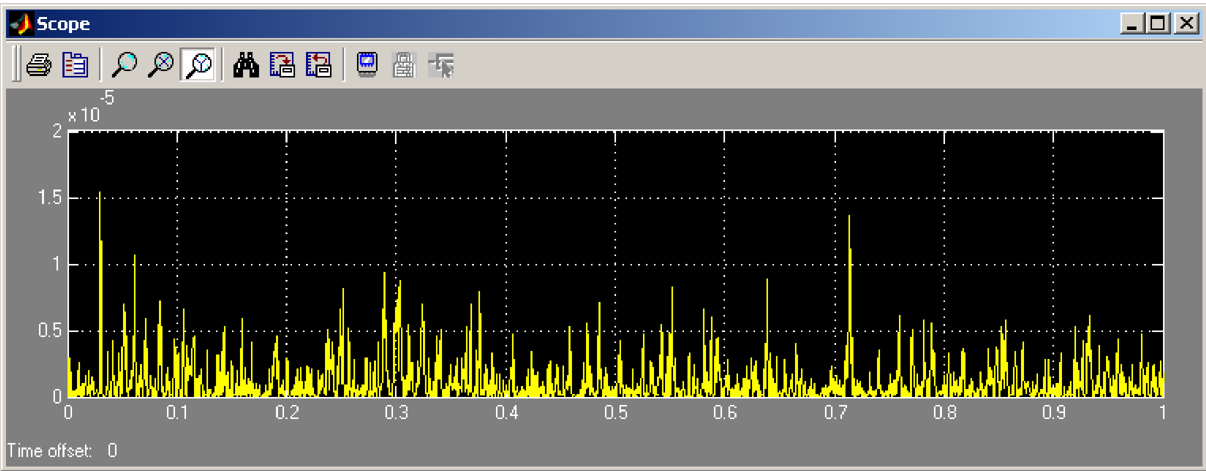

Figure 6-1: Simulated time history over one second of null depth variations on the Astrium nulling breadboard for closed-loop OPD control for measured OPD fluctuations due to air turbulence. For more than 90 percent of the time the null depth is below 3 ppm.

7 Phase 2 Achievements

In Phase 2 the focus of the activities was primarily placed on the establishment of optical designs and on corresponding optical models for different candidate DARWIN nulling interferometer concepts.

Initially, an optical design for the Bow-Tie configuration has been created. The Bow-Tie concept has however been given up on ESTEC side in favour of the X-Array configuration. Therefore a new optical design for the X-Array has been elaborated and implemented in BeamWarrior and FINCH.

The simulations performed with the X-Array configuration revealed a severe problem with polarisation rotation that led to a substantial deterioration of the nulling performance. This problem was identified to be generic for all types of nulling interferometers with a more than one-dimensional beam routing. The pragmatic solution chosen for the remainder of this study was to suppress this polarisation effect by assuming idealised surface properties for certain mirrors in the optical set-up. With this simplification a corresponding BeamWarrior model of the X-Array has been set up and similarly a FINCH model. For illustration, two conjugate polychromatic transmission maps calculated with the FINCH model are shown in Figure 7-1.

Occasionally of FINCH progress meeting 2 in November 2004 it became clear that the X-Array was on ESTEC side no longer the favoured configuration. Astrium declared its willingness to once more change the configuration and consequently thereafter an optical design for the equilateral TTN+ configuration has been developed (cf. Figure 7-2) and modelled with BeamWarrior and FINCH. The resulting TTN+ performance has been simulated assuming an inter-spacecraft distance of 25 m. A modulation map of the TTN+ calculated with the FINCH model is shown in Figure 7-3.

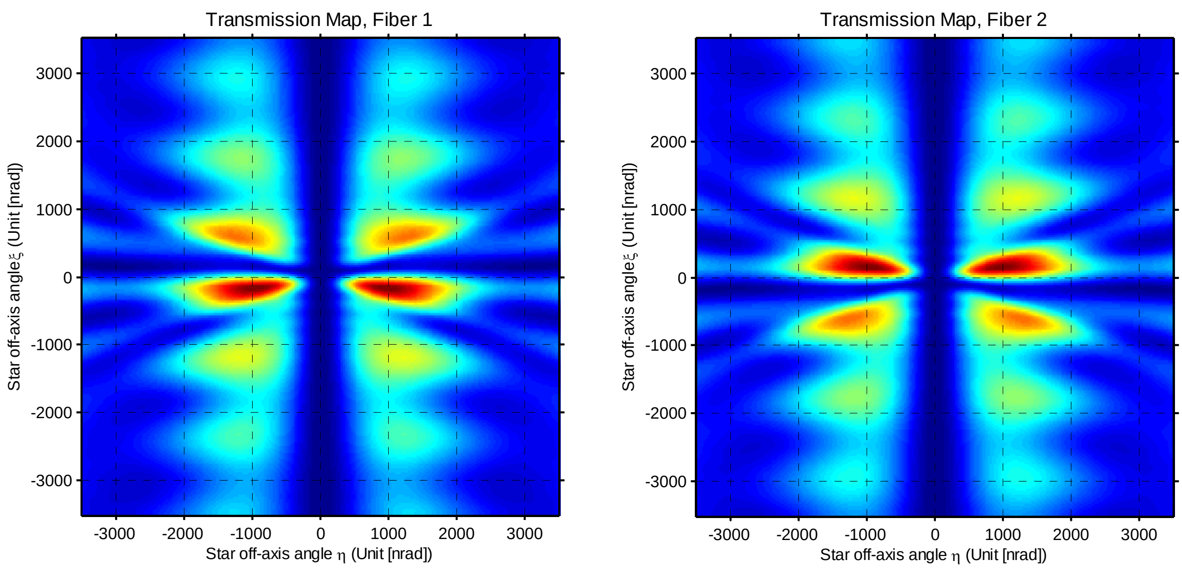

Figure 7-1: The two conjugate polychromatic transmission maps calculated with FINCH for the X-Array nulling interferometer configuration.

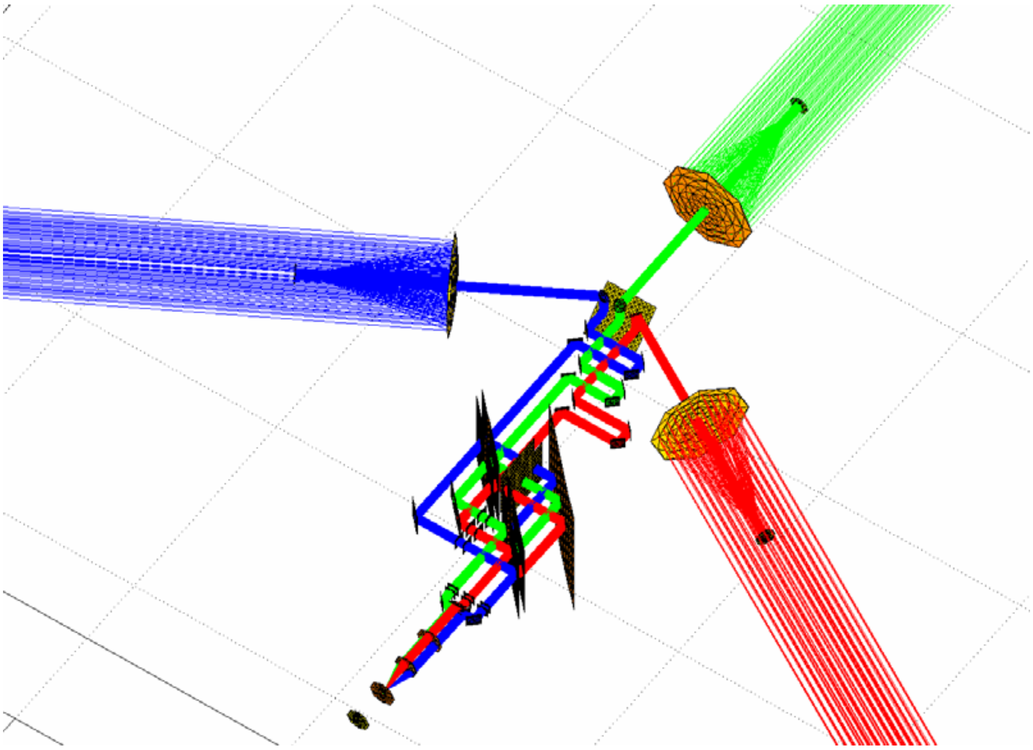

Figure 7-2: BeamWarrior visualisation of the central beam recombination optics designed for the equilateral TTN+ configuration with multi-axial fiber coupling.

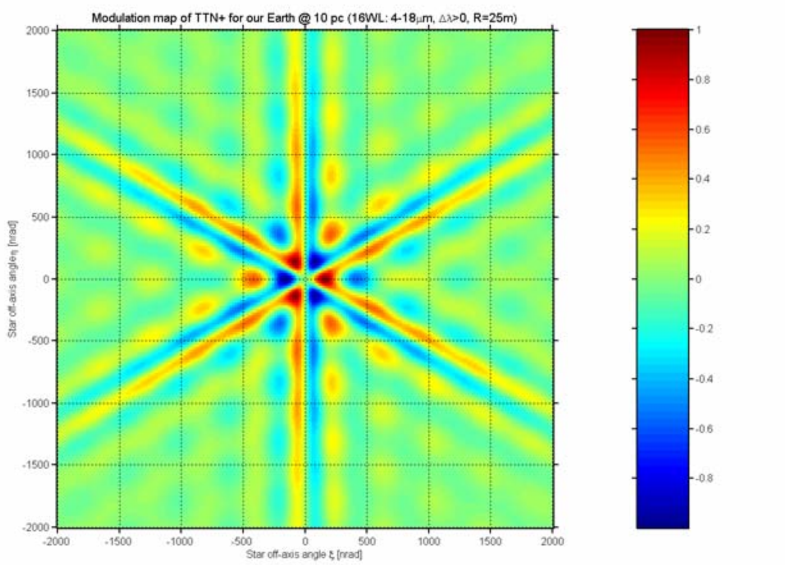

Figure 7-3: Modulation map of the equilateral TTN+ for our Earth as seen from 10 pc and represented by 16 sub-bands from 4 to 18 µm as calculated using FINCH. The modulation map is obtained by subtracting from the transmission map of sub-interferometer 1 that one of sub-interferometer 2. The Earth's radiance is derived from a blackbody with T=255 K.

In parallel to the design, modelling and analysis of different nulling interferometer configurations a significant further tool development has been accomplished.

The BeamWarrior functionality has been extended in many areas. Only a few shall be highlighted hereafter:

- New optical surface to model wave-plates and polarisers
- New optical surface to induce arbitrary aberrations in a beam
- New capabilities to model higher-order aspherical surfaces
- Extended capabilities to define obscuration masks
- New propagation option for the angular spectrum method allowing to propagate strongly converging or diverging fields

All new functionalities have been documented in the BeamWarrior User Manual.

FINCH has been extended to allow for simulation of the interferometer response to spatially extended celestial sources (cf. Figure 7-4). Moreover one of the computational bottlenecks in the FINCH model, the algorithm used for propagation through the single-mode fiber and its injection optics, has been significantly accelerated (by a factor of four) and its accuracy improved.

In order to increase the flexibility of FINCH models, similar sub-models have been grouped together in the form of configurable subsystems. Their reconfiguration, i.e. the exchange of one sub-model by another one can now be performed by means of script files.

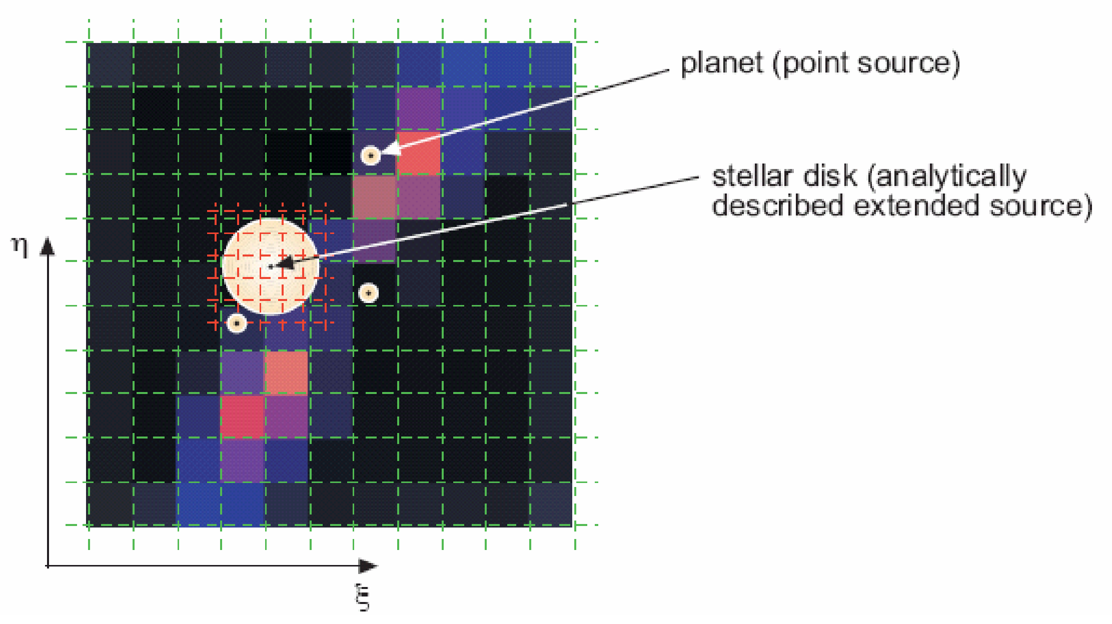

Figure 7-4: Example of a celestial scene consisting of a stellar disk, of three planets and of a background distribution decomposed in FINCH into a set of point sources.

For BeamWarrior and FINCH shared repositories have been created that allow access from different sites. In the moment this is used to harmonise the development going on in parallel in Astrium and ESO. But in principle, this service may be used in future by the whole DARWIN community.

The regression testing for new BeamWarrior versions is now automated by a dedicated regression testing tool.

Finally, a two-day FINCH training session for two ESTEC members has been held at Astrium's premises in mid 2005.

8 Conclusions and Recommendations

The optical part of FINCH is now in pretty good shape. It allows for reliable modelling and simulation of a large family of different DARWIN nulling interferometer concepts and is able to represent the optical chain between a given celestial observation scene and the science or metrology detector readings resulting from it.

The optical modelling approaches used in FINCH have been carefully validated in the instance of Astrium's nulling breadboard by comparison of measurements performed on the real hardware and simulation results. The analysis and implementation of different DARWIN candidate nulling interferometer concepts (Bow-Tie, X-Array, TTN+) resulted in new insights and a deeper understanding of the intricacies of this challenging mission. An important problem identified in this way is the severe reduction in null depth due to polarisation rotation.

The FINCH/OPT models have been found to be rather accurate but computationally demanding. This is problematic in case of large observation scenes consisting of many source points. It is therefore desirable to speed up those models. A corresponding novel modelling approach developed in Phase 2 of this study unfortunately proved to be not easily applicable for DARWIN and had to be given up. A new approach has been devised meanwhile but requires further consolidation.

In order to allow for a seamless processing flow in the DARWIN simulation, the interfaces between FINCH on one side and the pre- and post-processing tools ORIGIN (for scene generation) and FITTEST (for planet identification) on the other side need to be harmonised.

Summarising, a very powerful optical simulation tool has been created in the framework of this study. The usage of the tool is far from being simple. It necessitates the intelligent, knowledgeable user in order to produce meaningful results. No tool ever is perfect. So is FINCH. Therefore routes for further development have been shortly addressed.