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PHASES: Opto-mechanical solutions to perform absolute spectrophotometry from space

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Abstract. This work provides an update of the current status of PHASES, which is a project aimed at developing a space-borne telescope to perform absolute flux calibrated spectroscopy of bright stars. PHASES will make it possible to measure micromagnitude photometric variations due to, e.g., exo-planet/moon transits. It is designed to obtain 1% RMS flux calibrated low resolution spectra in the wavelength range 370–960 nm with signal-to-noise ratios >100 for stars with V<10 in short integration times of ∼1 minute. The strategy to calibrate the system using A-type stars is outlined. PHASES will make possible a complete characterization of stars, some of them hosting planets. From the comparison of observed spectra with accurate model atmospheres stellar angular diameters will be determined with precisions of ∼0.5%. The light curves of transiting systems will be then used to extract the radius of the planet with similar precision. The demanding scientific requirements to be achieved under extreme observing conditions have shaped the optomechanical design. A computational model and a high-precision interferometric system have been developed to test the performance of the instrument.

1. INTRODUCTION

PHASES (Planet Hunting and AsteroSeismology Explorer Spectrophotometer; see [2] and [3]) consists of a modified Baker telescope with a primary mirror of 20 cm in diameter feeding two systems: the integrated tracking camera, which achieves a pointing stability of $0.2''$, and the spectrophotometer. It has been designed to be housed in a microsatellite launched into a low-earth Sun-synchronous orbit. The science goals of the mission require spectrophotometry from space to measure light variations with ultra-high precision and obtain absolute flux calibrated spectra of bright stars. As a first step, the optical design was developed with the main goal of avoiding stray light on the science detector.

The preliminary optical design of PHASES and the calibration strategy were described in [2]. The strategy of the mission and three different proposals for the opto-mechanical design were presented in [3]. This paper is mainly devoted to update the current status of the opto-mechanics of PHASES. The mission and calibration strategies are outlined in Section 2. In Section 3 the laboratory tests to verify and improve the opto-mechanical performance of the instrument are discussed.

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2. THE MISSION

PHASES is designed to obtain time series of spectra in the wavelength range 370–960 nm with a resolving power ranging from 900 (at 370 nm) to 200 (at 960 nm). Series of absolutely calibrated spectra of bright stars would be routinely obtained. PHASES is designed to get 1% RMS flux calibrated spectra with signal-to-noise ratios >100 for stars with $V<10$ in integration times <1 minute. This is extremely useful for a deeper characterization of stars with or without activity, and the study of known transiting planetary systems (including fortuitous discoveries of large moons).

In [2] and [3] a more complete description of the mission is presented; here a summary is given. The most time-consuming programmes will be related to the study of transits and astroseismology. The list of targets for the transit programme will be extracted from the *Extrasolar Planets Encyclopaedia* (*exoplanet.eu*), where currently 20 host stars have $V<10$ and PHASES' orbit permits the observation of half of them, including the 5 brightest targets. For those host stars it would be possible to derive light curves with a photon-noise-limited photometric precision below 11 parts per million from the observation of spectra time series during two transits (assuming a duration of $\sim$4 hours each). The planet's radius would be accurately ($<1\%$ RMS) determined from the depth of the light curve and the stellar radius, which can be coherently obtained from the out-of-transit absolute spectrophotometry and available parallaxes (Hipparcos and, in the near future, Gaia).

2.1 In-orbit calibration strategy

White dwarfs with pure-hydrogen atmospheres are excellent calibration sources but too faint to be observed in reasonable times with PHASES. A-type stars, whose spectral shape is also dominated by H opacity, are also useful astronomical sources for calibration. The spectrum of Vega, an A0V star, is well mimicked by plane-parallel line-blanketed LTE models (see [1]). PHASES will be calibrated from observations of A-type stars since they provide excellent results (see [2] and [3]).

3. LABORATORY TESTS: STUDYING THE PERFORMANCE OF THE OPTO-MECHANICS

PHASES must remain in focus while operating in a continuously changing thermal environment on a LEO orbit with 822 km of altitude. In order to minimize the effect of a rapid thermal change, the design and material selection of the telescopes' opto-mechanical components is a key factor in meeting the science objectives. The most common designs to reduce the effects of a thermal change are a single material design and a low coefficient of expansion (CTE) design. The subject of this research is a self-compensating design applied to an off-axis mirror system like that of PHASES.

In a standard on-axis system a self-compensating truss is routinely achieved by the use of different materials with complementary CTE's ([6]). In an off-axis system there is a dramatic increase in the complexity of the compensating design as distances between multiple elements and the angular relationships between the mirror planes must be controlled. This is achieved by way of a series of truss elements in a space-frame design. The CTE's of the truss elements are carefully matched to produce the desired effect for a given temperature range. Our method of design offers the possibility of introducing the mirror specifications for any instrument (not only PHASES) in order to generate a *drop in* compensated solution. This has the added benefit of an increased technology readiness level and can shorten the cycle times of other missions ([5]).

3.1 Computational analysis: Modelling the instrument

As described in paper [3] a combination of software packages is used to design and test the off-axis truss design. The software is used to structurally and thermally analyse the deformations in the model to

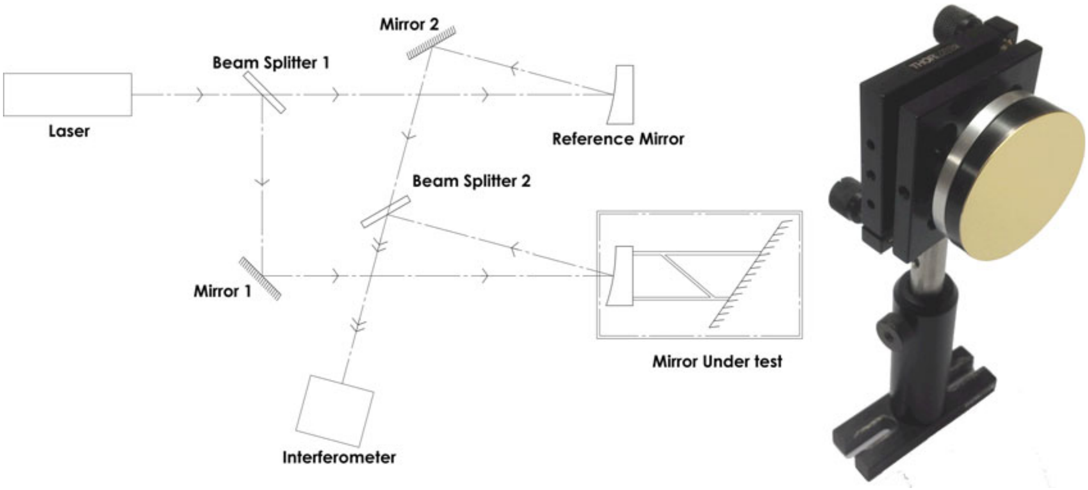

Figure 1. Layout of the off-axis Michelson interferometer (left) and mirror under test (right).

find an optimum solution. However, with the transfer of different file formats occurring multiple times during the computational analysis, and the computational error that exists in any theoretical approach, it is necessary to prove that the method of analysis is accurate to within the instrument acceptable error tolerances during operation. Our approach is to model representative elements of PHASES and empirically verify it by means of controlled optical tests.

3.2 Optical Testing: An interferometric system to verify the mirrors' form

As PHASES is an off-axis system, an aluminium 15 deg off-axis parabolic mirror with a diameter of 50.8 mm and a focal length of 508 mm (seen in Fig. 1, right) was chosen as the subject of the optical tests. The off-axis parabolic nature of the mirror allows us to quantify any form error caused by a change in temperature.

In Fig. 1 (left) the simplified layout for a 15 deg off-axis spatially filtered modified Michelson interferometer is shown. The interferometer uses two off-axis mirrors, one is used as a reference while the other is used as the test mirror. In this configuration, Beam Splitter 1 splits the beam between the Reference Mirror (RM) and, via a folding mirror (Mirror 1), the Mirror Under Test (MUT). The beam from the RM is folded using Mirror 2 while Beam Splitter 2 recombines the beams creating an interference pattern.

When heat is applied to the truss structure supporting the MUT the relative change in distance can be precisely measured by counting the number of fringes. The software model must be calibrated and the error in angular, linear and lateral displacement along with form error need to be established. To perform this, the test set-up should permit isolated displacement along any single axis. The MUT is mounted on a high precision translation stage (5 μm increments) and moved mechanically along the relevant axis to calibrate the interferometer setup. Then, the MUT is mounted on a simple truss and is used to calibrate the computational model. To facilitate this it must be possible to control the temperature of the MUT and truss. Thus, a thermal chamber was mounted on the optical bench. Two thermoelectric generators (TEG's) are used to heat the chamber volume and thermocouples are used to constantly monitor the temperature. The chamber has a 53 mm opening on one side to allow the beam enter the chamber. In addition to the thermal chamber the mirror and truss elements can also be directly heated either individually or together. Figure 2 shows the mirror mounted to a resistive element and in turn onto a kinematic mirror mount. This is connected to the three truss elements via ceramic isolators,

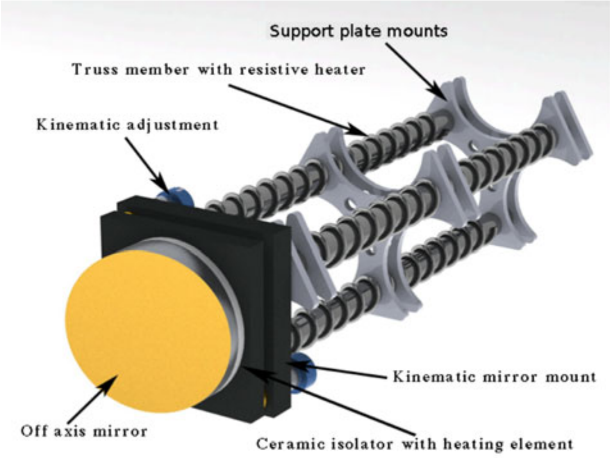

Figure 2. Off-axis mirror mounted on simple truss.

which significantly reduce heat transfer between the truss and the mirror. The three truss elements are directly heated by resistive coils. By heating all three elements linear movement is achieved while tilt can be achieved by heating any one of the elements individually.

Each set of optical tests are carried out a number of times to improve their accuracy. Results for the computational model and the optical tests are compared for each given set. If it is found that the model is not performing within the required operational tolerances, the model is further refined and the set of tests are run again. This is an iterative process and builds on each set of results until the required level of accuracy is achieved.

On completion of the current testing, the next step is to manufacture an off-axis truss similar to the one between PHASES' tertiary mirror and the detector. This truss is designed using the computational model and will be tested in the same manner as the simple truss. If the computational model performs satisfactorily, production of a final computational design method can be realised. As the truss system is very similar between each off-axis mirror pairing (i.e. between the primary and secondary mirrors and the secondary and tertiary) the application of the truss design to each paring is a realistic goal. This method can then be applied to the full optical design for PHASES telescope. On manufacture of the PHASES mirrors further investigation can be undertaken to optically test the entire system.

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