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An empirical approach for space-based mirrors to evaluate the extent of radiation compaction under expected environmental doses

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Abstract:

ZERODUR®, a glass-ceramic by SCHOTT, has a successful 50-year heritage of stability in critical mirror substrates of astronomical payloads used in various orbits. This heritage includes the Hubble Space Telescope (secondary mirror) that celebrated its 30 year-in-space anniversary, and the Chandra Great Observatory (all mirrors). Although ZERODUR® exhibits a strong record of dimensional stability under orbital ionizing radiation, prior dosage measurements exhibit considerable disagreement on the magnitude of dimensional change under irradiation, and extrapolation to the level of realistic dosages presents large uncertainty. This has resulted in users of ZERODUR® needing to apply large error budget allocations for radiation effects. Our intent is to conduct rigorous measurements, matched to compaction theory, and extend measurement into lower doses realistic to mirrors in telescopes. Detailed models have been constructed, coupons designed in collaboration with the irradiation facility of the metrological institute Physikalisch-Technische Bundesanstalt (PTB) and precision optical metrology defined by Arizona Optical Systems (AOS). We will describe the models, the coupons manufacturing, the irradiation plan, and the plan defining measurement of curvature and shape change due to irradiation. The measurement data will be reconciled against the FEM results to refine accuracies in modeling. Accurate measurement in a stable set-up enables quantitative results at realistic dosages.

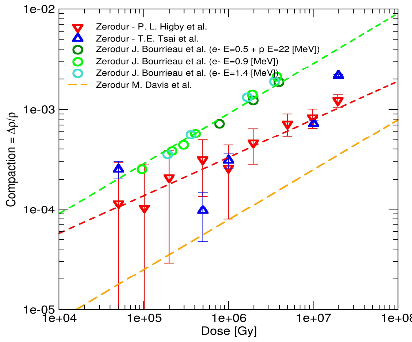
I. Ionizing radiations & compaction

Satellites are subject to ionizing radiations. These irradiations are due to charged particles travelling at relativistic energies. The energy deposited by these particles into any given materials induces local defects and change *de facto* the material properties. These local changes depend on the flux of ionizing particles (*i.e.* the type of orbits and mission duration) as well as the type of material under consideration.

Spaceborne optics must be form stable over time in order to ensure the best possible image rendering. Consequently, reflective optics are mostly made of close to zero expansion materials in order to mitigate the effect of local temperature gradients on the optical figure.

Besides temperature gradient, gradient of total ionizing doses are also suspected to deform the optics via a so-called compaction effect (material density shrinkage quantified $\Delta\rho/\rho$). The effect of this contribution is highly debated and different phenomenological compaction laws have been proposed in the past, however no consensus have been met so far.

In this work we aim at proposing a refined compaction law for the optical material ZERODUR® based on precise dosimetry and precise interferometric metrology.



Compactions laws of Zerodur® proposed by different research group. Note the lack of consistency.

II. Coupon design & manufacturing

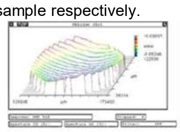
For this study, coupons have been designed in two geometries:

- Ø=50 [mm] x 5 [mm] (25 pieces)
- Ø=50 [mm] x 2 [mm] (25 pieces)

The induced stress resulting from the dose-deposition could drive to some breakages. In order to prevent it, we purposedly reduce the sub-surface damages (SSD). To this end we CNC machined the pieces with a fine grain diamond tool. The front and back surface have been polished, while the polishing and the walls and the chamfers have been acid etched in order to remove the remant SSD.

Typically achieved a λ/6 and λ/20 (see picture) surface error for the 2 [mm] and 5 [mm] sample respectively.

Pieces as delivered to AOS prior to the polishing / coating and metrology steps.



Interferogram performed after the polishing / coating phase @ AOS

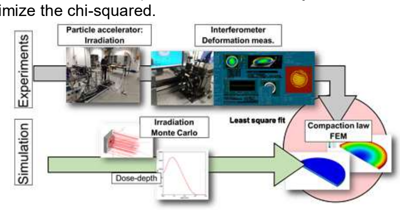
III: New compaction law: Methodology

Compaction laws have been derived using two main approaches:

1. By measuring the density changes over a bulk material having been homogeneously irradiated:
   This approach requires large samples and long exposure time under gamma irradiation in order to achieve an acceptable level of accuracy.
2. By measuring the vertex radius of curvature of discs having been heterogeneously irradiated:
   Practically, this approach is more simple and precise than the former one, however it requires a good mathematical description of the dose field and consequently of the strain field within the material.

In this work we will investigate the compaction phenomenology following the second approach, however, contrarily to similar past works carried out using this method we will describe all the fields (dose –strain) necessary for the derivation of the compaction law by means of more accurate computational approach (Monte Carlo and FEM).

The compaction law will be determined using a least square fitting approach, the computationally determined radius of curvatures will be compared to the experimental ones and the parameters of the compaction law will be adjusted in order to minimize the chi-squared.



Faraday cup designed for the irradiation of the 2 and 5 [mm] discs.

IV. Irradiation setup

The irradiation will be performed at the research linear accelerator of the Metrological Electron Accelerator Facility (MELAF) of the Physikalisch-Technische Bundesanstalt (PTB).

- The energy of the electrons used for the irradiation will be 0,5 and 1,5 MeV;
- The electron beam is pulsed with a typical pulse width of 2.5 µs;
- An Integrating Current Transformer (ICT, Bergoz Instrumentation) is installed at the end of the accelerator beamline for non-destructive charge measurement of the electron pulses for beam monitoring.
- At the end of the accelerator beam line the collimated electron is then scattered by a 50 µm titanium foil. The scattered radial electron profile is phenomenologically described by a Gaussian.
- The samples are held in a Faraday cup (FC), by means of the FC it is then possible to determine the fraction of e- being fired onto the coupons.

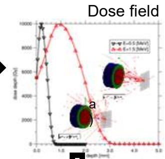
Faraday cup designed for the irradiation of the 2 and 5 [mm] discs.

V. Numerical simulations:

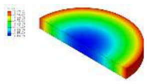
Monte Carlo:

The total ionizing dose deposited into the material has been simulated using the Geant4 software package.

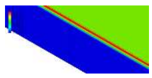
Dose field



Deformation field



Strain field



FEM

The calculated dose-depth is then converted by means of a compaction law into a strain field. The relaxation of this strain-field is then numerically computed using ANSYS, the deformation of the surface is then described by means of Zernike polynomial.

Least square fitting criterion:

The compaction law will be determined iteratively following the step a)→b)→c) by means of a least square optimization. The corresponding χ^2 is defined below:

$$\chi^2 = \frac{1}{N}\sum_{i=1..N}\left[Pow_i^{exp} - Pow_i^{sim}(\{A_p;B_p\},D_i(z))\right]^2$$

With:

- N: Being the number of samples into consideration;
- i: an index denominating a given sample;
- Pow: meaning the estimated power;
- The superscript exp and sim designate the origin of the data, respectively experimental or simulated;
- The doublet in brace $\{A_p;B_p\}$ corresponds respectively to the prefactor and exponent of the power law used for describing the compaction, $\frac{\Delta\rho}{\rho}(z) = AD(z)^B$ with $D(z)$ the dose deposited at a given depth z. The subscript p indicates the iteration level of the algorithm.

VI Outlook & perspectives

Summary:

An advanced methodology has been defined in order to quantify the effect of compaction resulting from a strain – dose gradient.

Characterization dose-profile and Sagitta evaluation will be enhanced by means of:

- Monte Carlo simulation of the deposited total ionizing dose and precise measurement of the charge collected on the target;
- Parametrical FEM simulation of the discs using a power law binding the calculated dose to the expected Power generated over the surface of the samples.

Perspectives:

The least square fitting of a compaction law based on experimental determination of the radiation induced Sagitta and simulation results will be started within the next trimester. The results will be provided in further communications.