Phasing a Segmented Space Telescope

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Abstract: We present a paradigm for phasing a segmented, sparse space telescope. We optimize the contrast of the image of the scene, by using a stochastic search algorithm: simulated annealing. We have built laboratory models with multiple actuators, and achieved convergence within hours. The system is robust and fully autonomous.

Space telescopes: Because of launcher size and mass limitations, future large space telescopes need to be segmented. During deployment, it is expected that the segments and secondary mirror will fold out, but the placement accuracy is orders of magnitude lower than the one-tenth wave expected. For earth observations, flux is high enough to reduce or remove some segments, making deployment even simpler.

Alignment: When segments are adjacent, mechanical and optical sensors can measure their mutual displacement. This solves part of the problem, but still we need to measure the wave front, for example by a Hartmann-Shack slope sensor. Unfortunately, wave front slopes, measured on the non-contiguous aperture, cannot be integrated. On the other hand, image sharpness criteria allow to reduce the wave front errors. Since the search space for the optimal solution is huge, we reverted to stochastic optimization. Optimization has another advantage, where the deployment is not fully successful (e. g. a jammed actuator), since the algorithm will find the best solution for the existing case.

Simulated annealing: This is a random optimization search, mimicking the process of annealing of materials [1, 2]. We start with a high "temperature" where all segment actuators make large random deviations. The we slowly "cool" the system by reducing these motions. In parallel, we initially accept all improvements to the image sharpness (usually its standard deviation) and reject only a few reductions in image contrast. With "temperature" decrease, we become less tolerant to bad moves and reject almost all of them. It can be shown that when the cooling rate is slow enough, one is assured of a true global optimum.

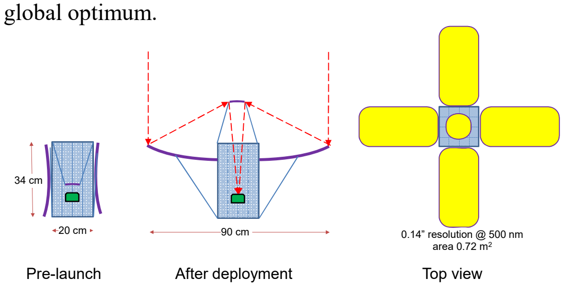

Fig. 1. Example of a nano-satellite of 12U volume (16Kg) space telescope. After deployment, resolution is high, despite the limited collection area.

Experiment: We built three models in the laboratory (Fig. 2) to test both the alignment algorithm and the hardware response. Initial placements were random, around 1 mm. Each one of the four segments had three actuators behind it, totalling twelve degrees of freedom. The algorithm first aligns, on its own, the four images on top of each other ("stacking"), namely it corrects segments' tips and tilts. It then searches for fringes between these images ("phasing"). Both operations, stacking and phasing, increase the total image contrast, in accordance with the optimization.

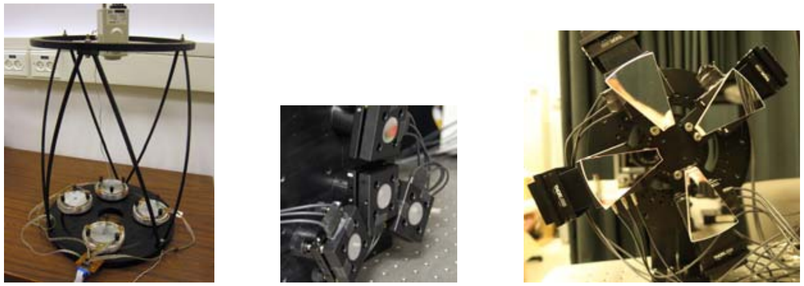

Fig. 2. Three generations of the lab models. The first two used round and spherical mirrors, but because of spherical aberrations were too wieldy. The last one is made of a parabolic mirror, cut into segments. In all models, the segments were placed in non-redundant spacings to improve the modulation transfer function.

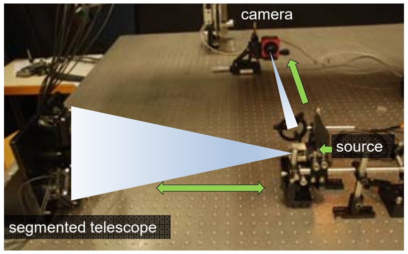

Fig. 3. Optical setup. The source beam diverges onto the segmented telescopes. Since all segments share the same spherical center, they all converge back to it, then get diverted to a magnifying lens and a camera. In the segmented parabola model we replace the source with a collimated beam, but the rest of the system is the same.

Results: Sooner or later, the system converges to the best possible image. For sources (Fig. 3), we used lasers, LEDs, white light "stars" and even extended scenes, and they all converged (Fig. 4). For the most complex cases, the solution was achieved after about twenty hours, mostly limited by the Ethernet camera response time [2, 3]. This is a fully acceptable time for space telescopes.

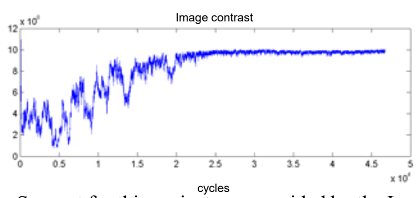

Fig. 4. Typical convergence curve. We use the standard deviation of the image as our cost function. During the first part, there are more excursions to sub-optimal solutions, but in the end it asymptotes to the best solution.

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