Ultra-violet compact telescope mission

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Ultra-violet mission

• Wish:
  • Observe above the atmosphere

• Reasons:
  • Avoid atmospheric opacity
  • Avoid atmospheric turbulence

• Limitations:
  • Cost
  • Availability
  • Time to launch

• Solution (partial):
  • Employ small satellites
Bigger telescopes: weight and volume

• The width/thickness ratio for telescopes apertures is ~10
• This is a major problem for ground telescopes, and much more for space
• Using light-weight mirrors reduces their mass
• Segmenting the main aperture reduces their volume and mass even further
• Folding/deploying the aperture significantly reduces launch volume
How to fit a telescope on a cubesat

• Example: 12U (16 kg)

pack’n’go  after deployment  sky view

0.028" resolution @ 100 nm
area 0.72 m²

Tel Aviv, 12 July 2017  Ultraviolet Sky Surveys
Bigger telescopes: definition of the problem

• Segmented telescopes need alignment after deployment
• For segmented telescopes, the problem becomes more complex
  • Deploying the segments into their initial position
  • Fine tuning (phasing) the segments into their exact position
• What is the best way to measure the misalignment?
Traditional adaptive / active optics system
Novel adaptive / active optics system
Measurement methods

- Wave front sensors
  - Slope: interferometer, lenslet array
  - Curvature

- Wave front sensors require:
  - Separate optics, separate camera
  - Point source (star, ground beacon)
  - Compact or high-contrast source possible

- Measurement using the telescope camera
  - Optimisation: simulated annealing, phase diversity
  - Does not require separate detector
  - Point source, or high-contrast compact source
  - Iterative and slower

(JPL NASA – Northrop-Grumman study)

Tel Aviv, 12 July 2017
Wave front sensor

- Hartmann-Shack wave front sensor: sample the wave front by pinholes or lenslets
- Measure the lateral focus motions: gradients of the wave front
- Assumes contiguous aperture

Measured wave front gradients

\[ S = F \nabla \phi = F \left( \frac{\partial \phi}{\partial x}, \frac{\partial \phi}{\partial y} \right) \Rightarrow \phi(x, y) \]
Deformable mirror types

a. piston activation: flat mirrors

b. piston activation: continuous mirror

c. monolithic mirror

d. electrostatic membrane mirror

e. bending moments using pistons

f. bimorph mirror

(Deformable Mirrors, Ribak 1993)
Deformable mirrors

• Main types
  • Membrane pushed and pulled by back-side actuators
    • Susceptible to print-through of actuators, if too thin
  • Thin membrane supported on the outside, non-contact actuation
    • Electrostatic actuation
    • Electromagnetic actuation
    • Piezoelectric actuation
    • Peripheral bending moments
  • Segmented nano-mechanical mirror

• Large choice of mirrors from sources abroad
  • USA, France, Netherlands, Russia, etc.

• Space persistent, but...
  • Launch of thin membranes to be qualified
  • Membranes must not resonate in space
  • High voltages and currents for various actuators
Optimisation

• Image Sharpness as a quality measurement of the optical accuracy
  • $\int I^2(u,v) du dv$ shown analytically to improve with wave front (Parseval)
  • Has many local minima.

• Stochastic optimization algorithm suggested:
  • Simulated Annealing (Ribak, Lipson, Adler, 1990)
  • Stochastic Parallel Gradient Descent (SPGD) (Vorontsov 1998)
  • Genetic Algorithm (Yang & Chen 2006)

• Common method today
  • “Sensorless adaptive optics”
    • No separate wave front sensor
  • Very successful in ocular optics,
  • Tens of papers (Zommer, Ribak, Lipson, Adler, 2006)
Simulated annealing

• The algorithm is named for the annealing process of metal.
  • Slowly cooling from the melting point allow relieve of stresses.
  • Allow diffusion of atoms to remove dislocations.
  • Directs the material into homogenous structure.
  • Creates long-distance correlations.

• The algorithm main advantages
  • Efficiently search within a large parameters space.
  • Efficiently overcome local minima.

• Here we employ the algorithm in hardware

(Kirkpatrick et al. 1983)
Algorithm

1. Initiation:
   - Defining effective temperature \( T_0 \)
   - measuring the energy (cost function) at starting point \( \vec{V} \)

2. Measuring the energy at nearby point \( \vec{V} + \Delta \vec{V} \). \( \Delta E \) is the energy difference.

3. Accept the step if \( \exp \left( -\frac{\Delta E}{T} \right) > \text{random number [0..1]} \)
   - If \( \Delta E \) is negative, the step is accepted always.
   - Else, there is always a chance for acceptance (depending on temperature).

4. Repeat steps 2+3 several times.

5. Lower the temperature. Go to step 2.

6. Keep on until stopping criteria.
Looking for the minimum
Optimising the optimisation

- **Annealing Schedule** –
  - Slow enough schedule leads to a better solution
  - At high temperature – random walk behavior
  - At low temperature – greedy search, and then freezing.
  - The algorithm is most efficient at intermediate temperatures

- **Scheduling rules to set:**
  - Number of steps at the same temperature.
  - Decreasing temperature by:

- **Stopping criterion**
  - Minimal conversion
  - Number of steps exceeded

\[
T_{i+1} = A^2 T_i \quad \text{if acceptance} > 0.7
\]
\[
T_{i+1} = A^{0.3} T_i \quad \text{if acceptance} < 0.7
\]

\[A \sim 0.9995\]
Autonomous telescope alignment

• Problem:
  • Segments of telescope are not aligned after deployment
  • Some of the segments are omitted to reduce weight, volume
  • No known means to measure the non-contiguous segments

• Solution:
  • Use a small bright object as target
  • Employ telescope camera as sensor
  • Contrast of object rises as alignment improves
  • Use stochastic search (simulated annealing) to reach the global solution

• Realization:
  • Successful simulations in white light
  • Successful laboratory simulation with four small mirrors

Phasing the sparse telescope: simulation

Unfilled telescope aperture yields proper images
Phasing the sparse telescope: experiment

- 4 spherical mirrors
- 3 actuators each
- Extended white object
Interference between panels

• Here we are using a light-emitting diode (LED)
• We obtain interference fringes among the four images, one through each panel
• These fringes are visible in the Fourier transform of the image
• As annealing proceeds, we see more and more coherence between panels
Secondary alignment

- Secondary can move in $x$-$y$-$z$-$\theta$-$\phi$

- No matter which position we start at, we always end at the same result
Element alignment, single telescopes

Telescope # one:
Five degrees of freedom

Telescope # two:
Seven degrees of freedom

initial

final
Summary

- We developed a method to align a segmented, sparse telescope
- The method is based on simulated annealing in hardware
- The segmentation enables employing a small satellite
- After launch and panels’ deployment, we still obtain
  - enough photons for spectroscopy
  - high resolution as if from a larger full aperture
- In case of malfunction, the final image is optimised for the actual shape
- For a few segments, each with 3 DoF, annealing takes a few hours
The End