

# Spaceborne intensity interferometry via spacecraft formation flight

Erez N. Ribak<sup>\* a, c</sup>, Pini Gurfil<sup>b, c</sup>, and Coral Moreno<sup>c</sup>

<sup>a</sup> Physics Department; <sup>b</sup> Faculty of Aerospace Engineering; <sup>c</sup> Technion Autonomous System Program,

Technion – Israel Institute of Technology, Haifa 32000, Israel

## ABSTRACT

Interferometry in space has marked advantages: long integration times and observation in spectral bands where the atmosphere is opaque. When installed on separate spacecraft, it also has extended and flexible baselines for better filling of the  $uv$  plane. Intensity interferometry has an additional advantage, being insensitive to telescope and path errors, but is unfortunately much less light-sensitive. In planning towards such a mission, we are experimenting with some fundamental research issues. Towards this end, we constructed a system of three vehicles floating on an air table in formation flight, with an autonomous orbit control. Each such device holds its own light collector, detector, and transmitter, to broadcast its intensity signal towards a central receiving station. At this station we implement parallel radio receivers, analogue to digital converters, and a digital three-way correlator.

Current technology limits us to  $\sim 1$ GHz transmission frequency, which corresponds to a comfortable 0.3m accuracy in light-bucket shape and in its relative position. Naïve calculations place our limiting magnitude at  $\sim 7$  in the blue and ultraviolet, where amplitude interferometers are limited. The correlation signal rides on top of this huge signal with its own Poisson noise, requiring a very large dynamic range, which needs to be transmitted in full. We are looking at open questions such as deployable optical collectors and radio antennae of similar size of a few meters, and how they might influence our data transmission and thus set our flux limit.

**Keywords:** Stellar Interferometry, Intensity Interferometry, Satellites, Flight formation

## 1. INTENSITY INTERFEROMETRY

Newer and better optical stellar interferometers are being built and upgraded constantly<sup>1</sup>. Their accuracy improves and their sensitivity increases, even if at a slow pace. However, efforts to apply this technology to space have not been successful. The current requirements of sub-micron accuracy and stability, and large collecting area, among others, have been shown in the laboratory to be solved, but were unsuccessful in transformation to space. We have looked at an alternative solution, namely employing an intensity interferometer in space.

Stellar Intensity Interferometry (*II*) was developed in order to solve the problem of measuring the angular size of extremely small bright stars. *II* main advantages are that it is almost unaffected by large baselines and it is less susceptible to the Earth's atmosphere. *II* was invented by Robert Hanbury Brown and Richard Twiss<sup>2</sup> who implemented it in 1956. The *II* was operated in Narrabri, Australia, until 1972. The technique has never been used since then, but there are recent attempts to renew it in practice by piggybacking on existing collector arrays<sup>3-6</sup>.

## 2. WHY GO TO SPACE

The next place to try *II* is space, with large collectors as independent separate units. We are actively investigating and developing algorithms and lab technologies that will ultimately enable space-borne *II*. The main advantages of launching an *II* into space are:

1. Availability of shorter wavelengths (blue to UV), absorbed or scrambled by the atmosphere, and therefore not covered by amplitude stellar interferometry (the leading technology today from the ground). Shorter

---

\* eribak@physics.technion.ac.il; phone +972 4 8292 776

wavelengths signifies higher resolution at any given baseline, and observation of objects not available from the ground, especially at high resolution.

2. Larger obtainable baselines between the optical collectors will provide higher resolution. Large ground interferometers reach hundreds of meters today, but in space the sky is not the limit.
3. Flexibility in moving collectors and thus adding baselines will improve the final image quality. Better  $uv$  coverage is possible by having many collectors and by changing their relative position with respect to each

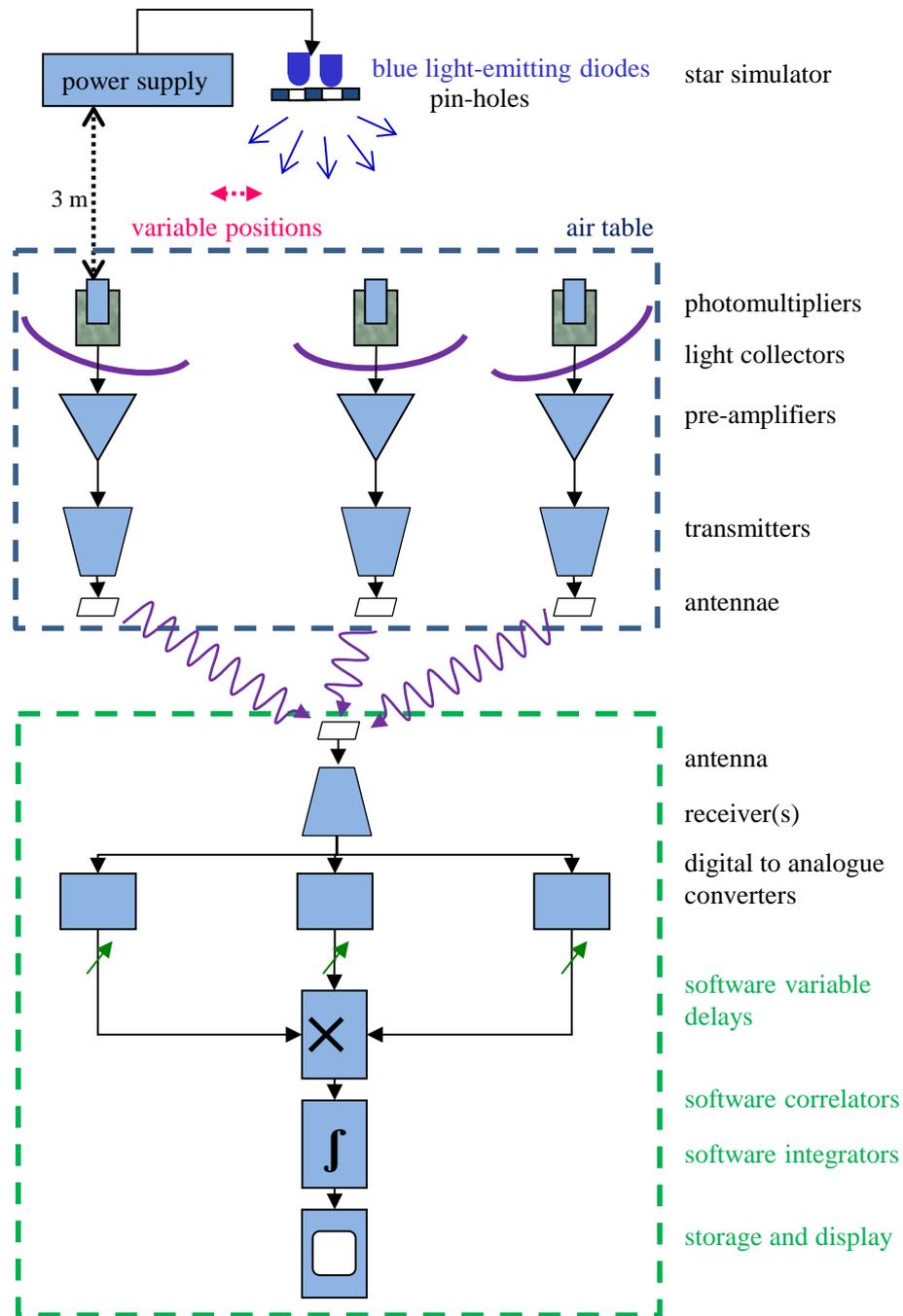


Fig. 1: Scheme of the laboratory model intensity interferometer.

other, and not having to rely on earth rotation to do this for us. Positioning commands are simply sent out by the central control<sup>7</sup>.

4. Larger light collectors than affordable on the ground. Not having to withstand winds and gravity, and being limited to 0.3 m accuracy, we can design for much more collection area.
5. Collector position needs to be known only down to the bandwidth used, orders of magnitude lower than direct interference of electromagnetic fields.
6. Increased integration times will reduce the noise in the images. While on the ground we are limited either by atmospheric turbulence or transmission stability (in amplitude interferometers), and in daily cycles, in space we can keep the detectors essentially running for very long times.
7. There is no need to transfer photons between telescopes: it suffices to transmit their intensities by radio.
8. Each light collector (and of course their combination) can also double up as a spectrometer, again in wavelengths that are not easily available.



Fig. 2: Nanosatellite model. From top: photomultiplier (centre) and antenna (closer), light-collecting dish, tilt mechanism, signal preamplifier and transmitter, rotation propellers.

We also expect problems and limitations, some of them very basic:

1. The signal-to-noise ratio, which is barely acceptable in amplitude interferometry, is much worse in  $II$ . The fact that we are dealing with second order correlation of the fields, rather than their first order correlations as in amplitude interferometry, introduces a huge bias even before we start. Instead of measuring the normalized mutual coherence function  $\gamma^{(1)}(u, v)$ , we measure  $\gamma^{(2)}(u, v) = 1 + |\gamma^{(1)}(u, v)|^2$  in which the phase is lost (The spectral correlation has the same attributes<sup>5</sup>).
2. We cannot measure objects that are resolvable by the dishes themselves, which means (like in radio interferometry) that we have a severe shortage on low spatial frequencies.
3. We are limited in bandwidth by the transmission of the signals from space to ground, and we need to have reliable (and hence large) radio dishes to relay these signals to the central correlator.
4. Multispectral measurements cannot be correlated as such, as each requires its own channel. As bandwidth limits us in passing a single spectral channel, many channels become even more difficult.

5. Image reconstruction from three or more baselines is more difficult due to the loss of phase, and hence to phase closure and other image clues. However, there is a number of algorithms which are successful in overcoming this issue<sup>11</sup>.



Fig. 3: Air table facility. Three nanosatellite (partial) models are placed on the table. Both “star” and radio receiver are installed ~3m above the centre of the table.

### 3. INITIAL TESTS

We have started to investigate and develop technologies that will ultimately enable space-borne *II* (Fig. 1). We make use of the Distributed Space Systems Laboratory (DSSL) at the Asher Space Research Institute at the Technion. We started to build a distributed *II* using the nanosatellite models. This system of satellites constitutes a dynamic autonomous multi-agents robotic system.

The nanosatellite models levitate on an air-bearing table to simulate a micro-gravity environment. The air-bearing table reliably simulates space dynamics, since the satellites move on a space-like orbital plane. Air bearing spacecraft simulators have been used for nearly 50 years worldwide<sup>9</sup>.

The fields of distributed and cooperative robotics emerged in the late 1980s and have grown dramatically since then<sup>10</sup>. We have constructed nanosatellite robotic models which are being used in this research. Currently there are three nanosatellites (Fig. 2). Each satellite includes four motors with an electronic speed control, navigation and control unit, rechargeable battery, accelerometer, gyro, magnetometer and laser range finder. In order to track the satellites, a camera and image processing software are used. A wireless serial communication system (XBee) is used for connecting the nanosatellite control channel to the control computer. The nanosatellites levitate on an air-bearing table as shown in Fig. 3. The table provides a micro-friction environment for simulating the orbital motion of the nanosatellites.



Fig. 4: Intensity communication signal during testing. *Left:* Transmitters and antennae. *Right:* Receivers.

The optics part consists of two light-emitting diodes (LEDs) placed high above the air table in a dark room. These are masked by micron size pinholes in order to mimic a binary and test the system performance. Initially we used Fresnel lenses for light collection, and we switched to low-quality dishes. These can be tilted to view the light source above. The signal is detected by a photomultiplier and amplified before being sent to the transmitter.

There are three receivers and transmitters running at 0.95GHz bandwidth, at three separate frequency bands set around 3.1, 4.2 and 5.9 GHz bands (Fig. 4). These are fed to analogue-to-digital converters running at up to 5 giga-samples per second (GSPS), which in turn are fed into a Field-Programmable Gate Array (FPGA). Here correlations and integrations are performed and saved into the host personal computer (Fig. 5).

We are now at the stage of integrating all parts of the system and it seems like all components are responding as expected.

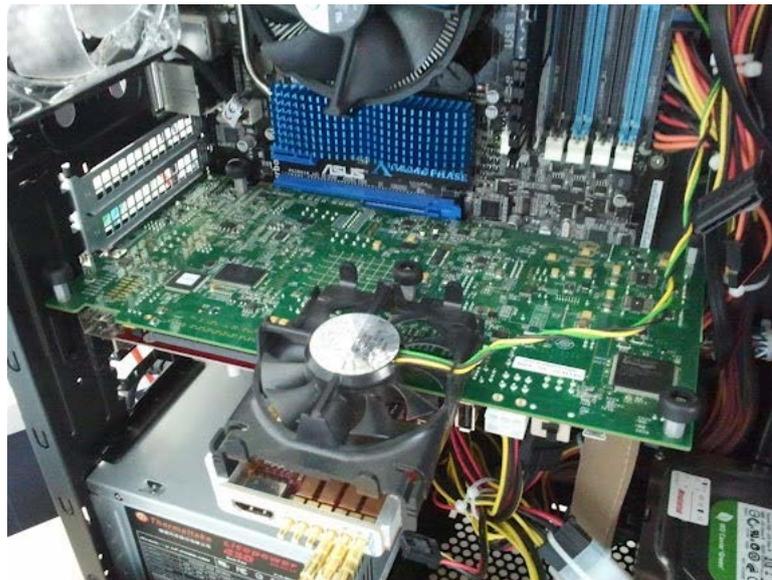


Fig. 5: Analog to digital converters and correlator. Converters can run up to 5 GSPS. The correlator is a Virtex-6 FPGA.

## 4. SUMMARY

Our experiment is meant as a lab demonstrator for a space intensity interferometer. Such an interferometer flown in formation should be easy to deploy and run, and should yield astronomical results in wave length bands and resolutions never tested. Potentially, and even for humble baselines, it could transcend existing interferometers in these aspects and at intensities close to those available to amplitude interferometry.

## 5. ACKNOWLEDGEMENTS

We are most grateful for the support of Hovhannes Agalarian, Maxim Rubanovich, Ludmila Kimelman, Reuven Bronstein at the Asher Space Institute, Shmuel Hoida, Steve Lipson and Dan Spektor at the Department of Physics, Moshe Namer, Haim Malka, Yuri Komorovsky, Erez Ben-Ari, Maxim Meltsin, at the Communication Lab - EE Department. Parts of this work were supported by the Israel Science Foundation, the Israeli Ministry of Science and the European Research Council.

## REFERENCES

- [1] Labeyrie A., Lipson S. G. and Nisenson P., [An Introduction to Optical Stellar Interferometry], Cambridge University Press, Cambridge, 316-320 (2006).
- [2] Brown R.H., [The Intensity Interferometer its Application to Astronomy], Taylor and Francis, London (1974).
- [3] LeBohec S., and Holder J., "Optical Intensity Interferometry with Atmospheric Cherenkov Telescope Arrays", *Astrophysical Journal*, 649, 399–405 (2006).
- [4] LeBohec S, Adams B, Bond I, Bradbury S., Dravins D., Jensen H., Kieda D. B., Kress D., Munford E., Nuñez P. D., Price R., Ribak E., Rose J., Simpson H., and Smith J., "Stellar intensity interferometry: experimental steps toward long-baseline observations", *Proc. SPIE 7734*, 77341D-77341D-12 (2010).
- [5] Dravins D., Jensen H., Lebohec S., and Nuñez P. D., "Stellar intensity interferometry: astrophysical targets for sub-milliarcsecond imaging", *Proc. SPIE 7734*, 77340A-77340A-12 (2010).
- [6] Dravins D., LeBohec S., Jensen J., Nuñez P. D., for the CTA Consortium, "Optical Intensity Interferometry with the Cherenkov Telescope Array", *Astroparticle Physics*, in press (2012).
- [7] Alfriend K. T., Vadali S. R., Gurfil P., How J. P., and Breger L. [Spacecraft Formation Flying: Dynamics, Control, and Navigation], Elsevier, Oxford, UK (2010).
- [8] Wang P. K. C., Yee J., Hadaegh F. Y. and Lau K., "Experimental Study of Formation Alignment of Multiple Autonomous Air-Levitated Vehicles with Rule-Based Controls", *Journal of Robotic System* 15, 559-580 (1998).
- [9] Schwartz J. L., Peck M. A. and Hall C. D., "Historical Review of Air-Bearing Spacecraft Simulators", *Journal of Guidance, Control, and Dynamics* 26, 513-522 (2003).
- [10] Liu J., and Wu J., [Multi-Agent Robotic System], CRC Press, USA (2001).
- [11] Nuñez P. D., Holmes R., Kieda D., Rou J., LeBohec S., "Imaging sub-milliarcsecond stellar features with intensity interferometry using air Cherenkov telescope arrays", *MNRAS*, accepted (2012).