



A Realistic Roadmap to Formation Flying Space Interferometry

John Monnier, Alicia Aarnio, Olivier Absil, Narsireddy Anugu, Ellyn Baines, Amelia Bayo, Jean-Philippe Berger, L. Ilseadore Cleeves, Daniel Dale, William Danchi, et al.

► To cite this version:

John Monnier, Alicia Aarnio, Olivier Absil, Narsireddy Anugu, Ellyn Baines, et al.. A Realistic Roadmap to Formation Flying Space Interferometry. Bulletin of the American Astronomical Society, 2019. hal-03058930

HAL Id: hal-03058930

<https://hal.science/hal-03058930>

Submitted on 12 Dec 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Astro2020 APC White Papers

A Realistic Roadmap to Formation Flying Space Interferometry

Type of Activity: ☐ Ground Based Project ☒ Space Based Project
☐ Infrastructure Activity ☒ Technological Development Activity
☐ State of the Profession Consideration ☐ Other _____

Principal Author:

Name: John Monnier
Institution: University of Michigan
Email: monnier@umich.edu
Phone: 734-763-5822

Endorsers: (names, institutions, emails)

Alicia Aarnio, University of North Carolina Greensboro, anaarnio@uncg.edu
Olivier Absil, University of Liège, olivier.absil@uliege.be
Narsireddy Anugu, University of Exeter, N.anugu@exeter.ac.uk
Ellyn Baines, Naval Research Lab, ellyn.baines@nrl.navy.mil
Amelia Bayo, Universidad de Valparaíso, amelia.bayo@uv.cl
Jean-Philippe Berger, Univ. Grenoble Alpes, IPAG, jean-philippe.berger@univ-grenoble-alpes.fr
L. Ilesedore Cleeves, University of Virginia, lic3f@virginia.edu
Daniel Dale, U. Wyoming, ddale@uwyo.edu
William Danchi, NASA Goddard Space Flight Center, william.c.danchi@nasa.gov
W.J. de Wit, ESO, wdewit@eso.org
Denis Defrère, University of Liège, ddefrere@uliege.be
Shawn Domagal-Goldman, NASA-GSFC, shawn.goldman@nasa.gov
Martin Elvis, CfA Harvard & Smithsonian, melvis@cfa.harvard.edu
Dirk Froebrich, University of Kent, df@star.kent.ac.uk
Mario Gai, Istituto Nazionale di AstroFisica, mario.gai@inaf.it
Poshak Gandhi, School of Physics & Astronomy, poshak.gandhi@soton.ac.uk
Paulo Garcia, Universidade do Porto, Portugal, pgarcia@fe.up.pt
Tyler Gardner, University of Michigan, tgardne@umich.edu
Douglas Gies, Georgia State University, gies@chara.gsu.edu
Jean-François Gonzalez, Univ Lyon, Jean-Francois.Gonzalez@ens-lyon.fr
Brian Gunter, Georgia Institute of Technology, brian.gunter@aerospace.gatech.edu
Sebastian Hoenig, University of Southampton, UK, s.hoenig@soton.ac.uk
Michael Ireland, Australian National University, michael.ireland@anu.edu.au
Anders Jorgensen, New Mexico Institute of Mining & Tech, Anders.M.Jorgensen@nmt.edu
Makoto Kishimoto, Kyoto Sangyo University, Japan, mak@cc.kyoto-su.ac.jp

Lucia Klarmann, Max-Planck-Institut für Astronomie, klarmann@mpia.de
 Brian Kloppenborg, Georgia Tech Research Institute, brian.kloppenborg@gtri.gatech.edu
 Jacques Kluska, KU Leuven, jacques.kluska@kuleuven.be
 J Scott Knight, Ball Aerospace & Technologies, jsknight@ball.com
 Quentin Kral, Paris Observatory/Lesia, quentin.kral@obspm.fr
 Stefan Kraus, University of Exeter, s.kraus@exeter.ac.uk
 Lucas Labadie, University of Cologne, Germany, labadie@ph1.uni-koeln.de
 Peter Lawson, Caltech, Jet Propulsion Laboratory, peter.r.lawson@jpl.nasa.gov
 Jean-Baptiste Le Bouquin, University of Michigan, lebouquj@umich.edu
 David Leisawitz, NASA GSFC, david.t.leisawitz@nasa.gov
 E. Glenn Lightsey, Georgia Institute of Technology, glenn.lightsey@gatech.edu
 Hendrik Linz, MPA Heidelberg, linz@mpia.de
 Sarah Lipsky, Ball Aerospace slipsky@ball.com
 Meredith MacGregor, Carnegie DTM, mmacgregor@carnegiescience.edu
 Hiroshi Matsuo, National Astronomical Observatory of Japan, h.matsuo@nao.ac.jp
 Bertrand Mennesson, JPL, bertrand.mennesson@jpl.nasa.gov
 Michael Meyer, University of Michigan, mrmeyer@umich.edu
 Ernest A. Michael, University of Chile, ernest.michael@raig.uchile.cl
 Florentin Millour, Université Côte d'Azur, florentin.millour@oca.eu
 David Mozurkewich, Seabrook Engineering, dave@mozurkewich.com
 Ryan Norris, Georgia State University, norris@astro.gsu.edu
 Marc Ollivier, Institut d'Astrophysique Spatiale Orsay, marc.ollivier@ias.u-psud.fr
 Chris Packham, UTSA, chris.packham@utsa.edu
 Romain Petrov, Côte d'Azur University, romain.petrov@unice.fr
 Benjamin Pope, New York University, benjamin.pope@nyu.edu
 Laurent Pueyo, STScI, pueyo@stsci.edu
 Sascha Quanz, ETH Zurich, sascha.quanz@phys.ethz.ch
 Sam Ragland, W.M. Keck Observatory, sragland@keck.hawaii.edu
 Gioia Rau, NASA/GSFC, gioia.rau@nasa.gov
 Zsolt Regaly, Konkoly Observatory, regaly@konkoly.hu
 Alberto Riva, INAF - Osservatorio Astrofisico di Torino, alberto.riva@inaf.it
 Rachael Roettenbacher, Yale University, rachael.roettenbacher@yale.edu
 Giorgio Savini, University College London, g.savini@ucl.ac.uk
 Benjamin Setterholm, University of Michigan, bensett@umich.edu
 Marta Sewilo, NASA/GSFC, University of Maryland, marta.m.sewilo@nasa.gov
 Michael Smith, University of Kent, m.d.smith@kent.ac.uk
 Locke Spencer, University of Lethbridge, Locke.Spencer@uLeth.ca
 Theo ten Brummelaar, CHARA - Georgia State University, theo@chara-array.org
 Neal Turner, Jet Propulsion Laboratory, Caltech, neal.turner@jpl.nasa.gov
 Gerard van Belle, Lowell Observatory, gerard@lowell.edu
 Gerd Weigelt, MPI for Radio Astronomy, weigelt@mpifr.de
 Markus Wittkowski, ESO, mwittkow@eso.org

Abstract:

The ultimate astronomical observatory would be a formation flying interferometer in space, immune to atmospheric turbulence and absorption, free from atmospheric and telescope thermal emission, and reconfigurable to adjust baselines according to the required angular resolution. Imagine the near/mid-infrared sensitivity of the JWST and the far-IR sensitivity of Herschel but with ALMA-level angular resolution, or imagine having the precision control to null host star light across 250m baselines and to detect molecules from the atmospheres of nearby exo-Earths. With no practical engineering limit to the formation's size or number of telescopes in the array, formation flying interferometry will revolutionize astronomy and this White Paper makes the case that it is now time to accelerate investments in this technological area. Here we provide a brief overview of the required technologies needed to allow light to be collected and interfered using separate spacecrafts. We emphasize the emerging role of inexpensive smallSat¹ projects and the excitement for the LISA Gravitational Wave Interferometer to push development of the required engineering building-blocks. **We urge the Astro2020 Decadal Survey Committee to highlight the need for a small-scale formation flying space interferometer project to demonstrate end-to-end competency with a timeline for first stellar fringes by the end of the decade.**

Caveats: The landscape of formation flying space missions is rapidly developing. In addition, some important relevant past missions are not well known and often were only sparsely described with few published results. The authors regret the inevitable incompleteness in trying to summarize an emerging field – please contact monnier@umich.edu with corrections and additions.

Key Science Goals and Objectives:

Long-baseline interferometry in the infrared and visible from the ground is now routine, obtaining images of stars and their environments with milli-arcsecond angular resolution, for instance rapidly-rotating stars (Monnier et al., 2007), magnetically-active stars (Roettenbacher et al., 2016), stars zipping around our galaxy's supermassive black hole (Gravity Collaboration et al., 2018a), galactic Novae exploding in realtime (Schaefer et al., 2014), a quasar's broad-line region (Gravity Collaboration et al., 2018b), and even exoplanet spectra directly (Gravity Collaboration et al., 2019). See Figure 1 for a gallery of recent interferometric imagery.

¹Here, smallSats are satellites with mass <180kg, including nanosats, cubesats, microsats, minisats, etc.

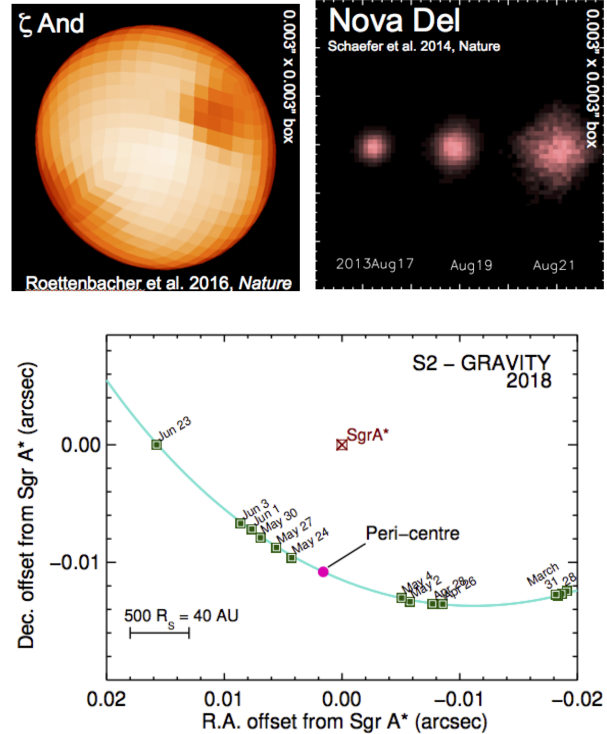


Figure 1: Ground-based infrared interferometry has come a long way in the past 20 years. Here we see some recent imaging results from Roettenbacher et al. (2016), Schaefer et al. (2014), and Gravity Collaboration et al. (2018a), spanning stellar imaging, novae explosions, and stellar orbits around Sgr A* that probe General Relativity. Note that the top two image boxes are only 3 *milli-arcseconds* across while the stellar orbit shown has errors <100 *micro-arcseconds*.

Despite these remarkable achievements, the sensitivity of this technique² is harshly limited by atmospheric turbulence – which restricts coherent integration times to $\ll 1$ second – and by the high price of large aperture telescopes – generally limiting most visible/IR interferometer facilities to $< 1.5\text{m}$ telescopes presently. For example, the CHARA interferometer has a limiting magnitude $K \sim 8$ with 1.0m telescopes in the near-IR while the VLTI can reach $K \sim 10$ with the 8m UT telescopes³. ALMA has shown us the power of combining the high angular resolution imaging of interferometry with a revolutionary boost in sensitivity. Ground-based facilities have matured to the point that planning can begin for the next generation of capabilities.

Figure 2 shows a simple reminder of why the allure of space interferometry is so great. The advantages of space over ground are fully realized: Sensitivity, Stability, and High angular resolution. The gains will be particularly dramatic in the mid- and far-infrared where existing techniques have left a huge gap in angular resolution and sensitivity.

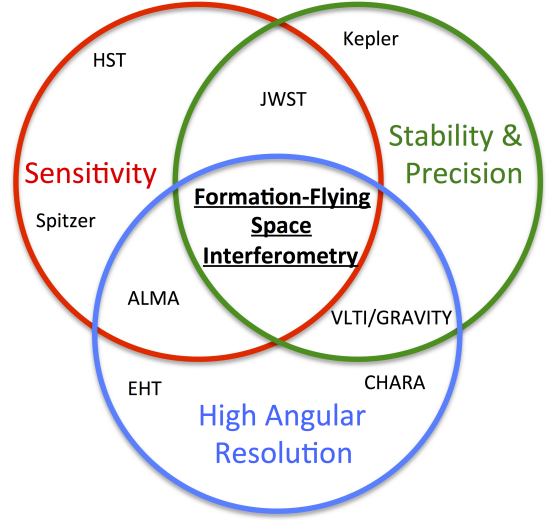


Figure 2: Space interferometry represents the ultimate astronomical observatory, capable of combining the power of sensitivity, stability and high angular resolution. Some of our most exciting astronomical goals require all three, namely mid-infrared exoplanet characterization using nulling or high-resolution image of high-redshift galaxies.

Planet Formation studies need milliarcsecond imaging across the IR

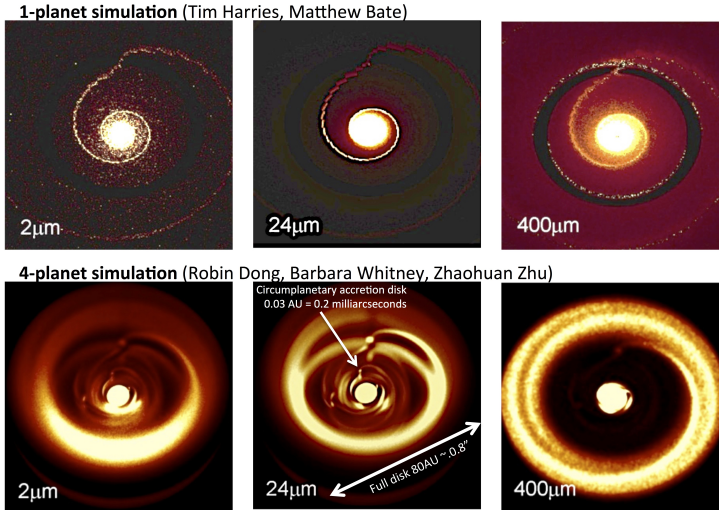


Figure 3: Multi-wavelength, milli-arcsecond resolution imaging will be needed to untangle the complex physical processes at play during planet formation, as this suite of simulations shows. Even more imaging complexity will likely be seen for extragalactic sources.

²We are specifically considering “direct detection” interferometry where photons have to be directly interfered using coherent beam transport using mirrors or single-mode fibers. Radio and mm-wave interferometry can use heterodyne detection and is far less limited by the atmosphere.

³VLTI/GRAVITY can observe $K \sim 17$ mag objects, such as flares around Sgr A*, as long as there is a bright phase reference source within a few arcseconds of the fainter target.

Planet-forming disks, for example, show a high level of complexity that we hope to understand with high resolution imaging across the IR. Figure 3 shows examples from a suite of simulations run as part of the Planet Formation Imager project studies (Monnier et al., 2018). We anticipate that high-redshift galaxies will also show a high level of structural complexity and a formation flying space interferometer would be a very powerful follow-up to expected exciting results from JWST.

Imaging complex sources such as galaxies and protoplanetary disks will require at least a dozen (or

more) telescopes in the interferometric array to synthesize complete (u,v)-coverage – recall that ALMA routinely uses ~ 50 antennas to create the breathtaking images of protoplanetary disks (e.g., D-SHARP; Andrews et al., 2018). A simpler space interferometer (e.g., LIFE, Large Interferometer for Exoplanets; <https://www.life-space-mission.com/>) with just 4x2.8m space telescopes spread over 500m could use nulling mid-IR interferometry for exoplanet detection and spectral characterization. Armed with decent knowledge of exoplanet demographics from Kepler, Kammerer and Quanz (2018) found that such an interferometer would detect hundreds of small planets. The detection statistics are very favorable and would highly complement the visible light exoplanet detections from a future HabEx or LUVOIR coronagraphy mission.

Please see additional relevant White Papers submitted to the ASTRO2020, including “Imaging the Key Stages of Planet Formation (lead: Monnier)”, “The Future of Exoplanet Direct Detection (lead: Monnier)”, and “A Long-Term Vision for Space-Based Interferometry” (Lead: Rinehart).

Technical Overview:

One can trace formation flying space interferometry proposals back to the 1970s and 1980s, including early work on nulling (Bracewell and MacPhie, 1979), a 3-telescope mission concept (TRIO; Labeyrie et al., 1984, 1985) and some interesting orbital mechanics considerations for low-earth orbits (Stachnik and Gezari, 1985). Ultimately the first optical interferometer in space was flown as part of a single telescope – the Hubble Space Telescope actually employs interferometers within the Fine Guidance Sensors (Eaton et al., 1993).

The first major push for a dedicated space interferometer was for **astrometry**, as atmospheric turbulence fundamentally limits the prospects for parallax and proper motions measurements on the full sky. Following encouragement from the 1990 Decadal survey, the Space Interferometry Mission (SIM, Shao, 1998) was developed by NASA, with a goal for 4μ -arcsecond astrometric precision using a 10m baseline on a structurally-connected interferometer⁴. Due to technical delays, rising costs, and emerging competing techniques, SIM was cancelled as part of the Astro2010 Decadal Survey.

High-precision astrometry using interferometers is technically difficult and has been largely abandoned in favor of more traditional architectures, relaxing stability constraints from nm-level to μ m level.

Table 1: Proposed space interferometer concepts (NASA/ESA)

Name	Wavelength	Reference
SIM	visible	Shao (1998)
OSIRIS	visible	Bagrov et al. (1999)
MAXIM	X-ray	Cash et al. (2004)
MAXIM Pathfinder	X-ray	Gendreau et al. (2004)
PEGASE	vis/NIR	Le Duigou et al. (2006)
SPECS	far-IR	Harwit et al. (2006)
ESPRIT	far-IR	Wild and Helmich (2008)
SPIRIT	far-IR	Leisawitz et al. (2007)
FIRI	far-IR	Helmich and Ivison (2009)
DARWIN	mid-IR	Cockell et al. (2009)
SIM-LITE	visible	Shao et al. (2010)
FKSI	mid-IR	Danchi and Barry (2010)
Stellar Imager	UV/visible	Carpenter et al. (2010)
TPF-I	mid-IR	Martin et al. (2011)
SHARP-IR	far-IR	Rinehart et al. (2016)
DARE	radio	Plice et al. (2017)
LISA	n/a	Amaro-Seoane et al. (2017)
SunRISE	radio	Lazio et al. (2018)
LIFE	mid-IR	Quanz et al. (2018)
IRASSI	far-IR	Linz et al. (2019)

⁴While there may be a short-term case for structurally-connected space interferometers, we are focused here in developing rationale for formation flying interferometry which is more promising the long-term.

Moving on, the next application explored seriously for space interferometry was **nulling for exoplanet detection**. Interferometric nulling (Bracewell and MacPhie, 1979) is the technique whereby the interferometer is tuned so that the host star sits at a destructive interference “null” while nearby exoplanets would generally not be nulled and thus be detected. Because light from the star is suppressed, there is no associated photon noise. Nulling has limited application on the ground due to the strong piston fluctuations induced by atmospheric turbulence that frustrate maintenance of the destructive null. In the 2000s, the NASA Terrestrial Planet Finder Interferometer (TPFI, Lawson et al., 2007) and ESA DARWIN (Cockell et al., 2009) projects studied the requirements for a mid-IR formation flying nulling space interferometer. The core idea is that an exo-Earth has the best contrast with the host star in the mid-IR ($1:10^6$, compared to $1:10^{10}$ in visible) and nulling will further suppress the host star flux. In mid/late 2000s, these technology projects failed to mature to funded flight missions – see Lawson (2009) and Lawson et al. (2017) for a timeline of events and an overview of technical achievements of the TPFI program.

Additional mission concepts have been developed for nearly all wavelengths ranges and also using unconventional methods such as intensity interferometry (Matsuo et al., 2018). A (nearly) exhaustive list of proposed major space interferometry mission concepts appears in Table 1.

Since cancellation of SIM, TPFI, and DARWIN, there has been only limited organized activity within NASA or ESA developing space interferometry. Fortunately, the technologies needed for formation flying were picked up by other programs (see Figure 4), either integrated into “smallSat” programs or as part of technology development for the LISA Gravitational Wave Interferometer Mission, which was recently given a huge boost by the detection of gravity waves by LIGO (Abbott et al., 2016). In the next section, we breakdown the subsystems needed for a formation flying space interferometer and introduce some recent relevant smallSat and larger missions.

Formation Flying Missions, *in theory and in practice*

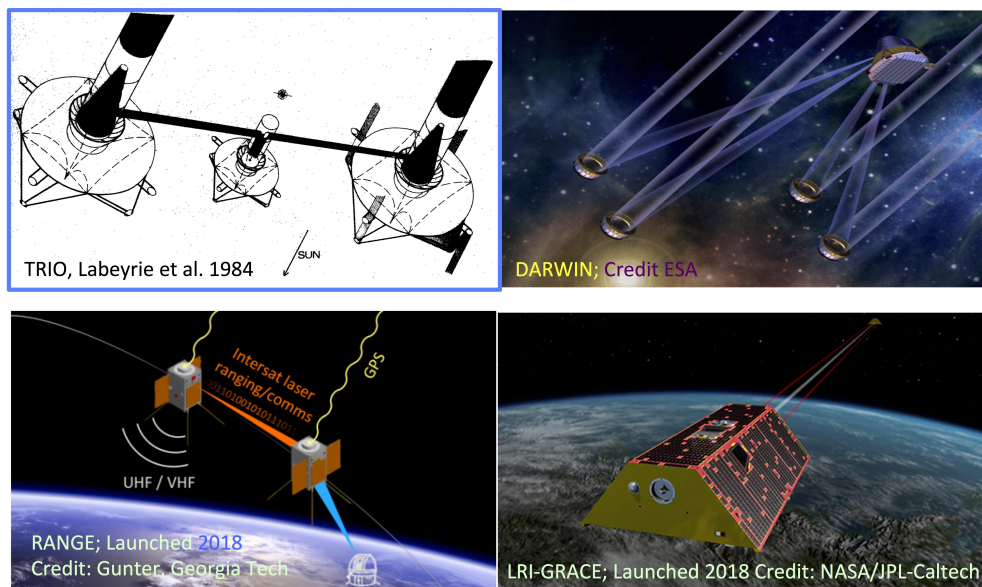


Figure 4: Astronomers have dreamed big for decades but are stalled in moving forward on ambitious space interferometers (top panels). Major breakthroughs in formation flying have been achieved by other communities (bottom panels), reinvigorating work towards true formation flying space interferometer with first stellar fringes by 2030.

Technology Drivers:

The number of small satellite projects worldwide is skyrocketing. Figure 5 shows the incredible growth in the field with over 4000 missions launched or in planning stages. While most projects have nothing to do with astronomy directly, astronomers have played major roles in some efforts, developing techniques for precision pointing and testing hardware such as cameras, detectors, fiber injection, and deformable mirrors. In this section, we explore how formation flying space interferometry can leverage progress across a spectrum of technologies and be realistically pursued in this decade.

It is beyond the scope of this white paper to go into detail about the Technical Readiness Level (TRL) of all required subsystems needed for a successful formation flying interferometer mission. However, we will discuss some of the key technologies and give a preliminary status report. We also present a reference list of relevant past, present and future projects (see Table 2). Readers should please contact the lead author at monnier@umich.edu with corrections and additions, as we intend this document to stay updated and available online following the ASTRO2020 process.

Astronomers might be curious why there has been so much recent technological development relevant to formation flying, outside the NASA/ESA interferometer context. Telecommunication and remote sensing communities have interests in the same technologies as well as specific interests in operation of “formations”, “swarms”, and “constellations” of satellites, be they nanoSats, CubeSats, microSats, or larger spacecraft. For example, absolute meter station keeping is desired for orbit maintenance of even loose constellations, involving space GPS or ground referencing. Basic maneuverability and propulsion systems are useful for changing orbits, re-pointing, and avoiding obstacles for a wide class of missions beyond strict formation flying. LIDAR and radio ranging are technologies needed for mapping Earth’s gravitational field or for future remote sensing missions, e.g., asteroids mapping, as well as for docking and rendezvous maneuvers.

Flying spacecraft within a formation < 1 km across can in principle allow high-speed communication through 5G wireless networks which can enable radically different instrument architectures. A “fractionated spacecraft” allows the different subsystems ordinarily contained on a single large, expensive spacecraft bus to be split into separate parts, allowing greater redundancy, cheaper replacements and sometimes fewer moving parts than traditional monolithic design. For example, a sunshield used for cooling could be positioned separately, a calibration target could be flown without needing awkward extending booms or other moving parts, and a high-gain antenna or high-bandwidth laser communication unit could be independent, relaying signals collected locally through the high speed local area network to ground stations. If a critical component fails, one can replace just the failed small satellite not an entire complex spacecraft.

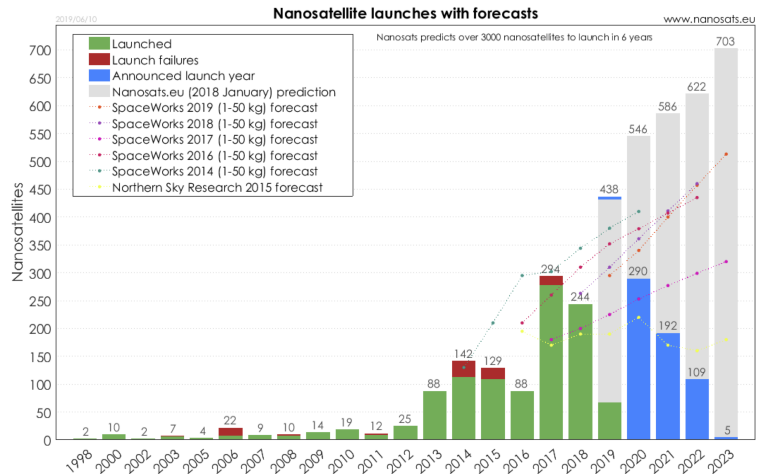


Figure 5: Around 1000 smallSats have flown so far with nearly 3000 in planning stages. There is truly an engineering revolution happening surrounding inexpensive small satellites making formation flying space interferometry feasible and exciting to pursue over the coming decade. This graph was generated at <http://www.nanosats.edu>.

Groups working with CubeSats have been pushing towards standardization of interfaces, underlying software architectures, miniaturization of key components such as propulsion valves, atomic clocks, LIDAR systems, etc. **A review of the field gives great optimism that most of the essential components for formation flying have been developed and tested in space already, although the need for consolidation and greater reliability remains.**

A realistic roadmap for formation flying space interferometry must include technology readiness in the following areas:

1. Launch vehicles and available orbits. SmallSats are carried into space by a wide variety of launch vehicles and generally travel on low earth orbits (LEO) between 400-550km with orbital decay lifetimes between 1-10 years. Wider orbits with longer lifetimes and higher orbital stability for the formation will ultimately be needed for space interferometry and additional study is needed to understand how to operate initial space interferometers from LEO. There may be new launch opportunities for lifting smallSats to near-GEO or lunar orbit in the future that could be transformative for a formation flying mission.
2. Post-release spacecraft stabilization (detumbling) and pointing acquisition. Small satellites can be tumbling wildly following deployment. Some mission failures still occur when trying to properly slow rotations, acquire a pointing reference and establish first ground communication. This area is rapidly maturing and we can expect that reliable, off-the-shelf solutions should be available for any future formation flying mission.
3. Communication with the ground. Science programs often generate large volumes of data which need high bandwidth ground communication. Radio downlink during limited time periods per day is the general strategy but laser communication is possible with speeds up to ~ 10 Gbits/sec. New planned satellite constellations (e.g., Starlink) providing high speed internet anywhere on (or just above) the Earth may be a game changer.
4. Communication between spacecrafts in-formation. Off-the-shelf Gigabit-speed local area networks based on 5G wireless technology are rolling out. The km-level range is a good fit for formation flying interferometers.
5. Power for smallSats is limited (~ 10 W) due to their small solar panels. More power will be needed for certain critical subsystems, e.g. laser communication and ranging. Deployable panels with greater collecting areas are being developed commercially (> 40 W) and may mitigate these issues in the medium-term.
6. Pointing, precision attitude control. Maintaining stable and smooth pointing is critical for nearly all astronomical applications. Recent missions have demonstrated arcsecond level pointing stability which should be (barely) adequate for formation flying of small apertures – especially in conjunction with field steering mirror feedback.
7. Monitoring absolute and relative distance between spacecraft. An overlapping hierarchy of technologies exist which allow us to know the 3D absolute and relative positions of a spacecraft formation. Off-the-shelf Space-GPS can provide sub-meter absolute positions with cm-level relative positions, adequate for monitoring orbit and for collision avoidance. For formation flying interferometry, we need to track separations within a wavelength of

light, well beyond mm ranging precision of state-of-the-art radio frequency ranging methods. Laser ranging has demonstrated spacecraft separations with precision down to the $\sim 10\text{nm}$ level and will be needed for formation flying interferometry.

8. Control and maneuverability, propulsion, orbit maintenance, formation rigidity. Propulsion is needed to change the baseline lengths between spacecrafts in an interferometer and also to maintain a fixed distance. A serious issue for formation flying spacing interferometry involves how to maintain optical path differences to allow phase-stable, long coherent exposures of interference fringes. Recent missions have maintained a formation with $\pm 0.5\text{ m}$ separations using active thruster feedback and drift speeds of $\sim 100\mu\text{m/sec}$ have been achieved. This performance is not adequate for formation flying interferometry and progress is needed in this area, including investigating chemical/monopropellant and electrical propulsion methods in addition to optimizing conventional cold gas thrusters. We can expect ongoing technical developments for LISA and others missions to advance this general area.
9. Re-positioning, re-fueling, rendezvous and docking. In addition to using propellant to maintain the array formation during observations, each new astronomical target will require globally re-orienting the array which is not possible with reaction wheels alone. The demands on propulsion will be high and limit both the achievable sensitivity and the lifetime of the mission. Alternative propulsion methods such as using solar pressure or atmospheric drag need to be explored for future formation flying. In the longer term the “propellant shortage problem” can be solved through regular robotic refueling, thus requiring rendezvous and docking development generally not considered for smallSats but which can have applications for assembling space structures beyond formation flying interferometers. Indeed, industry is pursuing on-orbit servicing capabilities both at GEO and LEO and we can reasonably expect remote re-fueling to be feasible on the decade time scale.
10. Algorithms for situational awareness, autonomy, safety. Spacecraft distances within 100m are considered very risky and generally avoided. If one loses control of a spacecraft in formation, there is a serious risk of collision and the generation of dangerous space debris. Development of robust autonomous control algorithms and “passively safe” formations are essential for future formation flying interferometers. On the software side there are connections with the active area of drone formation flying, situational awareness legacy from driverless cars, and past formation flying space missions.
11. Reliability. While it is widely acknowledged that component reliability has improved significantly in recent years, formation flying space interferometry will place huge new demands as the required number of working subsystems stack up.
12. General miniaturization and power reduction. University groups and companies are working to miniaturize a wide range of high-tech components that can be useful for modern instruments, for example lasers, atomic clocks, GPS hardware. 3D printing in plastic and metal has been a critical enabling technology for smallSats that allow optimal use of volume and mass and is accessible to small groups with limited budgets. These advances are critical and affect the panoply of technologies listed above. A future system-level review for a formation flying mission will need to identify key crucial technologies requiring further optimization.

13. Astronomy-specific challenges. So far we have hardly mentioned the unique astronomy requirements for formation flying space interferometry. University groups can have a huge impact here, while counting on the legion (thousands!) of other smallSat groups to continue perfecting general-purpose capabilities. We need to identify solutions for telescopes, automated high-efficiency fiber coupling, fine optical path length control to compensate for spacecraft drifts, beam steering and control, suitable “space-friendly” beam combiner designs, low power and space-qualified detectors, compact and low power cryogenics for eventual infrared work, sunshields for thermal management as well as control of scattered light, and evolve our thermal and vibration modelling capabilities. We expect participation at smallSat sessions at the biennial SPIE meetings to swell over the coming decade.

While smallSats can not accomplish all the ambitious science goals astronomers have, they offer a flexible and inexpensive prototype platform as a bridge to the \$1B missions we dream of. We will end this section with Table 2 – a partial list of mostly smallSat and some larger missions relevant to formation flying and space interferometry. While out of scope to present full discussion of each project, we do include noteworthy details about each mission in the table and a paper reference when available.

Table 2: Missions developing enabling technology for formation flying space interferometry

Name	Status	Primary Goal/s
Starlight (NASA-JPL)	cancelled 2002	Formation flying space interferometer (Blackwood et al., 2003)
TechSat-21 (AFRL)	cancelled 2003	Test formation flight technology
PRISMA (Sweden)	launched 2010	Autonomous formation flying, 800m-5km, $\pm 0.1m$ (Persson et al., 2010)
TanDEM-X (Germany)	launch 2010	Formation flying (Jäggi et al., 2012)
F6 (DARPA)	cancelled 2013	Fractionated free-flying spacecraft ($\$ > 200M$ spent)
CanX-4/5 (Canada)	launched 2014	GPS formation flying 50m-2300m separations Achieved positioning $\pm 0.5m$ w/cold gas (Kahr et al., 2018)
MMS (NASA)	launched 2015	GPS-assisted formation flying; 4.5km apart
MinXSS (Colorado)	launched 2016	Precision pointing (Mason et al., 2017)
OCSD-A (AeroSpace)	launched 2015	Laser communication &
& OCSD-B/C	launched 2017	Proximity sensing/maneuvering (Welle et al., 2018)
FLOCK 2p (Planet Lab)	launched 2017	Constellation phasing with drag (Foster et al., 2018)
RANGE (Georgia Tech)	launched 2018	Laser ranging, controlling formation actively
PICSAT (Obs. Paris)	launched 2018	Starlight injection into single mode-fiber; APD detector (Nowak et al., 2018)
ASTERIA (MIT-JPL)	launched 2018	Sub-arcsec pointing stability; $\Delta T \pm 0.01K$ (Pong et al., 2010)
GRACE-FO (NASA)	launched 2018	Laser ranging interferometry over 230km with $< 10nm$ precision (Abich et al., 2019)
DeMi (MIT)	to launch 2019	MEMS mirror testing (Allan et al., 2018)
TARGIT (Georgia Tech)	to launch 2020	LIDAR, ranging measurement of two spacecraft
PROBA-3 (ESA)	to launch 2020	Precision formation flying 150m apart Goal $\pm 5cm$ transverse positioning (Focardi et al., 2015)
FIRST-S (Obs. Paris)	TBD >2022	Interferometer on single spacecraft (Lapeyrere et al., 2018)
VTXO (NASA-GSFC)	TBD >2023	Formation flying (Rankin et al., 2018)
mDOT (Stanford)	TBD >2025	Formation flying (Koenig et al., 2015)
SunRise (NASA-JPL)	TBD >2025	GPS formation flying with 6 spacecraft; radio interferometry near GEO (Lazio et al., 2018)
LISA (ESA/NASA)	TBD >2034	Formation flying 2.5 million km apart (Danzmann and LISA Science Team, 2003)

Organization, Partnerships, and Current Status:

In addition to solving remaining technology issues, there are important management issues to consider. Hardware and software expertise for smallSats is distributed amongst a diverse group of small university groups, government labs, industrial partners both large and small, and spread over the world. Attempting formation flying space interferometry will require management of a loose-knit group of collaborators providing separate subsystems needing tight integration. This is further complicated by intellectual property issues and government rules restricting space technology information sharing. Formation flying space interferometry has a unique feature that helps organization since independent groups, even from different countries, can each be responsible for a separate spacecraft in the formation thus quarantining any IP and export licensing concerns to within each group. As ground-based interferometry is already very international, we anticipate fruitful international collaborations formed to tackle the exciting challenge of formation flying space interferometry using small satellites. We are aware of active interest to develop smallSat interferometry around the world, e.g., in the USA (Monnier), France (Lacour), and Australia (Ireland).

The convergence of multiple developments – exciting exoplanet science opportunities, the burgeoning smallSat revolution, LISA interferometer excitement, spiraling costs of NASA flagships – has fueled renewed interest in space interferometry in the astronomical community. At the 2018 SPIE Meeting in Austin, a splinter group organized an impromptu working lunch to begin planning a new future for space interferometry. This small group of ~10 persons represented USA, European and Australian Universities along with NASA Centers, STScI, and the US aerospace industry. In December 2018, the USRA organized a workshop with ~40 participants to reboot long-stalled efforts, revisit the science cases for space interferometry, and brainstorm new ways of going forward.

Beyond astronomy, the broader formation flying smallSat community is growing rapidly and with specialized workshops devoted just to formation flying engineering. We will start to see interferometrists at these meetings and begin converging on a baseline design for a first-generation formation flying space interferometer.

Schedule:

First fringes using a formation flying space interferometer should be demonstrated by 2030.

Cost Estimates:

For the topic of formation flying space interferometry, we are only proposing small satellite development over this decade, thus locating this effort firmly as a “Small <\$500M” space project.

Thousands of smallSat missions will occur over the next few years on a full range of topics, each developing important technology and maturing the smallSat ecosystem. We anticipate at least 3 small cubeSat missions (<\$5M) will narrowly focus on crucial gap technology needed for formation flying during the first half of next decade, followed by a mid-scale (\$20-50M) mission to actually interfere light collected by separate spacecraft to be launched by 2030.

Funding for smallSats can come from a variety of places, including NASA, NSF, DOD, AFRL, and industry. Some known funding programs are listed in Table 3. **NASA and NSF should increase funding for smallSat astronomy, an investment that could lead to transformative capabilities for decades to come.**

Table 3: Relevant Funding Programs for Formation Flying Space Interferometry (subject to change)

Program Name	Purpose	Project Budget	Cadence (if known)
NASA ROSES/APRA	suborbital, CubeSats	\$5M, up to \$10M	yearly, March
NASA Mission of Opportunity (MOO)	SmallSats	\$35M, up to \$70M	every ~2 years
NASA SMEX	small missions	\$180M w/ launch	every ~4 years (next 2019)
NASA Explorers	small/medium missions	\$350M w/ launch	every ~4 years (next 2021)
NASA Probes	large missions	\$1B	uncertain, >2022
NASA SIMPLEx	small/planetary	\$20-\$50M	
NASA ACT	components	\$1M-\$5M	
NSF Ideas Lab: Cross-cutting Initiative in CubeSat Innovations	CubeSat	\$4M	
Air Force Research Lab	smallSats	2 projects per year	next 2021
University NanoSat Program			

References

- Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., and Adhikari, R. X. (2016). Observation of Gravitational Waves from a Binary Black Hole Merger. *Phys. Rev. Lett.*, 116(6):061102.
- Abich, K., Braxmaier, C., Gohlke, M., Sanjuan, J., Abramovici, A., Bachman Okihiro, B., Barr, D. C., Bize, M. P., Burke, M. J., and Clark, K. C. (2019). On orbit performance of the GRACE Follow-On Laser Ranging Interferometer. *arXiv e-prints*, page arXiv:1907.00104.
- Allan, G., Douglas, E. S., Barnes, D., Egan, M., Furesz, G., Grunwald, W., Gubner, J., Haughwout, C., Holden, B. G., and do Vale Pereira, P. (2018). The deformable mirror demonstration mission (DeMi) CubeSat: optomechanical design validation and laboratory calibration. In *Proc. SPIE*, volume 10698 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 1069857.
- Amaro-Seoane, P., Audley, H., Babak, S., Baker, J., Barausse, E., Bender, P., Berti, E., Binetruy, P., Born, M., and Bortoluzzi, D. (2017). Laser Interferometer Space Antenna. *arXiv e-prints*, page arXiv:1702.00786.
- Andrews, S. M., Huang, J., Pérez, L. M., Isella, A., Dullemond, C. P., Kurtovic, N. T., Guzmán, V. V., Carpenter, J. M., Wilner, D. J., and Zhang, S. (2018). The Disk Substructures at High Angular Resolution Project (DSHARP). I. Motivation, Sample, Calibration, and Overview. *ApJ*, 869(2):L41.
- Bagrov, A. V., Boyarchuk, A. A., Barabanov, S. I., Mikisha, A. M., Rykhlova, L. V., and Smirnov, M. A. (1999). OSIRIS: An Optical Stellar Interferometer for Russian Investigations in Space. In Unwin, S. and Stachnik, R., editors, *Working on the Fringe: Optical and IR Interferometry from Ground and Space*, volume 194 of *Astronomical Society of the Pacific Conference Series*, page 381.
- Blackwood, G. H., Lay, O. P., Deininger, W. D., Gudim, M. A., Ahmed, A., Duren, R. M., Noecker, C., and Barden, B. (2003). StarLight mission: a formation-flying stellar interferometer. In Shao, M., editor, *Proc. SPIE*, volume 4852 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pages 463–480.
- Bracewell, R. N. and MacPhie, R. H. (1979). Searching for nonsolar planets. *Icarus*, 38(1):136–147.
- Carpenter, K. G., Schrijver, C. J., Karovska, M., Kraemer, S., Lyon, R., Mozurkewich, D., Airapetian, V., Adams, J. C., Allen, R. J., and Brown, A. (2010). Stellar Imager (SI): developing and testing a predictive dynamo model for the Sun by imaging other stars. *arXiv e-prints*, page arXiv:1011.5214.
- Cash, W. C., Gendreau, K. C., Shipley, A. F., and Gallagher, D. J. (2004). MAXIM Pathfinder: a practical configuration. In Citterio, O. and O’Dell, S. L., editors, *Proc. SPIE*, volume 5168 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pages 435–445.
- Cockell, C. S., Léger, A., Fridlund, M., Herbst, T. M., Kaltenegger, L., Absil, O., Beichman, C., Benz, W., Blanc, M., and Brack, A. (2009). Darwin-A Mission to Detect and Search for Life on Extrasolar Planets. *Astrobiology*, 9(1):1–22.
- Danchi, W. C. and Barry, R. K. (2010). The Fourier-Kelvin Stellar Interferometer (FKSI) - infrared detection and characterization of exozodiacal dust to super-earths: a progress report. In *Proc. SPIE*, volume 7734 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 77340M.
- Danzmann, K. and LISA Science Team (2003). LISA — An ESA cornerstone mission for the detection and observation of gravitational waves. *Advances in Space Research*, 32(7):1233–1242.

- Eaton, D. J., Whittlesey, R. A., Allen, B. W., Stoll, R., Abramowicz-Reed, L., and Margulies, M. (1993). On-orbit performance of the Hubble Space Telescope fine guidance sensors. *Appl. Opt.*, 32(10):1689–1695.
- Focardi, M., Bemporad, A., Buckley, S., O’Neill, K., Fineschi, S., Noce, V., Pancrazzi, M., Landini, F., Baccani, C., and Capobianco, G. (2015). Formation flying metrology for the ESA-PROBA3 mission: the Shadow Position Sensors (SPS) silicon photomultipliers (SiPMs) readout electronics. In *Proc. SPIE*, volume 9604 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 96040D.
- Foster, C., Mason, J., Vittaldev, V., Leung, L., Beukelaers, V., Stepan, L., and Zimmerman, R. (2018). Constellation Phasing with Differential Drag on Planet Labs Satellites. *Journal of Spacecraft and Rockets*, 55(2):473–483.
- Gendreau, K. C., Cash, W. C., Gorenstein, P., Windt, D. L., Kaaret, P., and Reynolds, C. (2004). MAXIM: the black hole imager. In Hasinger, G. and Turner, M. J. L., editors, *Proc. SPIE*, volume 5488 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pages 394–402.
- Gravity Collaboration, Abuter, R., Amorim, A., Anugu, N., Bauböck, M., Benisty, M., Berger, J. P., Blind, N., Bonnet, H., and Brandner, W. (2018a). Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole. *A&A*, 615:L15.
- Gravity Collaboration, Lacour, S., Nowak, M., Wang, J., Pfuhl, O., Eisenhauer, F., Abuter, R., Amorim, A., Anugu, N., and Benisty, M. (2019). First direct detection of an exoplanet by optical interferometry. Astrometry and K-band spectroscopy of HR 8799 e. *A&A*, 623:L11.
- Gravity Collaboration, Sturm, E., Dexter, J., Pfuhl, O., Stock, M. R., Davies, R. I., Lutz, D., Clénet, Y., Eckart, A., and Eisenhauer, F. (2018b). Spatially resolved rotation of the broad-line region of a quasar at sub-parsec scale. *Nature*, 563(7733):657–660.
- Harwit, M., Leisawitz, D., and Rinehart, S. (2006). A far-infrared/submillimeter kilometer-baseline interferometer in space. *New. Ast. Rev.*, 50(1-3):228–234.
- Helmich, F. P. and Ivison, R. J. (2009). FIRI—A far-infrared interferometer. *Experimental Astronomy*, 23(1):245–276.
- Jäggi, A., Montenbruck, O., Moon, Y., Wermuth, M., König, R., Michalak, G., Bock, H., and Bodenmann, D. (2012). Inter-agency comparison of TanDEM-X baseline solutions. *Advances in Space Research*, 50(2):260–271.
- Kahr, E., Roth, N., Montenbruck, O., Risi, B., and Zee, R. E. (2018). GPS Relative Navigation for the CanX-4 and CanX-5 Formation-Flying Nanosatellites. *Journal of Spacecraft and Rockets*, 55(6):1545–1558.
- Kammerer, J. and Quanz, S. P. (2018). Simulating the exoplanet yield of a space-based mid-infrared interferometer based on Kepler statistics. *A&A*, 609:A4.
- Koenig, A. W., D’Amico, S., Macintosh, B., and Titus, C. J. (2015). A pareto-optimal characterization of miniaturized distributed occulter/telescope systems. In *Proc. SPIE*, volume 9605 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 960514.
- Labeyrie, A., Authier, B., Boit, J. L., de Graauw, T., Kibblewhite, E., Koechlin, L., Rabout, P., and Weigelt, G. (1984). PM. 08 Trio: A Kilometric Optical Array Controlled by Solar Sails. In *BAAS*, volume 16, page 828.

- Labeyrie, A., Authier, B., de Graauw, T., Kibblewhite, E., and Weigelt, G. (1985). TRIO: a kilometric array stabilized by solar sails. In Longdon, N. and Melita, O., editors, *Kilometric Optical Arrays in Space*, volume 226 of *ESA Special Publication*, pages 27–33.
- Lapeyrere, V., Lacour, S., Crouzier, A., Nowak, M., Grenot, M., and Konig, P.-C. (2018). A space interferometer on a 6U Cubesat : FIRST-S. In *42nd COSPAR Scientific Assembly*, volume 42, pages E4.1–16–18.
- Lawson, P. R. (2009). Terrestrial Planet Finder: coda to 10 years of technology development. In Proc. SPIE, volume 7440 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 744002.
- Lawson, P. R., Lay, O. P., Johnston, K. J., and Beichman, C. A. (2007). Terrestrial Planet Finder Interferometer Science Working Group Report. Technical report.
- Lawson, P. R., Lay, O. P., Martin, S. R., Peters, R. D., Gappinger, R. O., Ksendzov, A. e., and Scharf, D. P. (2017). Technology challenges for exoplanet detection with mid-IR interferometry. In Proc. SPIE, volume 10566 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 105660V.
- Lazio, J., Kasper, J., Alibay, F., Lux, J., Hegedus, A., and Romero-Wolf, A. (2018). The Sun Radio Interferometer Space Experiment (SunRISE) Mission Concept: Development Status. In *42nd COSPAR Scientific Assembly*, volume 42, pages E1.8–20–18.
- Le Duigou, J. M., Ollivier, M., Léger, A., Cassaing, F., Sorrente, B., Fleury, B., Rousset, G., Absil, O., Mourard, D., and Rabbia, Y. (2006). Pegase: a space-based nulling interferometer. In Proc. SPIE, volume 6265, page 62651M.
- Leisawitz, D., Baker, C., Barger, A., Benford, D., Blain, A., Boyle, R., Broderick, R., Budinoff, J., Carpenter, J., and Caverly, R. (2007). The space infrared interferometric telescope (SPIRIT): High-resolution imaging and spectroscopy in the far-infrared. *Advances in Space Research*, 40(5):689–703.
- Linz, H., Bhatia, D., Buinhas, L., Lezius, M., Ferrer, E., Förstner, R., Frankl, K., Philips-Blum, M., Steen, M., Bestmann, U., Hänsel, W., Holzwarth, R., Krause, O., and Pany, T. (2019). InfraRed Astronomy Satellite Swarm Interferometry (IRASSI): Overview and study results. *Advances in Space Research*, in press:<https://doi.org/10.1016/j.asr.2019.06.022>.
- Martin, S., Ksendzov, A., Lay, O., Peters, R. D., and Scharf, D. P. (2011). TPF-Interferometer: a decade of development in exoplanet detection technology. In Proc. SPIE, volume 8151 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 81510D.
- Mason, J. P., Baumgart, M., Rogler, B., Downs, C., Williams, M., Woods, T. N., Palo, S., Chamberlin, P. C., Solomon, S., and Jones, A. (2017). MinXSS-1 CubeSat On-Orbit Pointing and Power Performance: The First Flight of the Blue Canyon Technologies XACT 3-axis Attitude Determination and Control System. *Journal of Small Satellites*, 6(3):651–662.
- Matsuo, H., Ezawa, H., Kiuchi, H., Honma, M., and Murata, Y. (2018). Proposal of Photon Counting Terahertz Interferometry. In *The Cosmic Wheel and the Legacy of the AKARI Archive: From Galaxies and Stars to Planets and Life*, pages 261–264.
- Monnier, J. D., Kraus, S., Ireland, M. J., Baron, F., Bayo, A., Berger, J.-P., Creech-Eakman, M., Dong, R., Duchêne, G., and Espaillat, C. (2018). The planet formation imager. *Experimental Astronomy*, 46(3):517–529.

- Monnier, J. D., Zhao, M., Pedretti, E., Thureau, N., Ireland, M., Muirhead, P., Berger, J. P., Millan-Gabet, R., Van Belle, G., and ten Brummelaar, T. (2007). Imaging the Surface of Altair. *Science*, 317(5836):342.
- Nowak, M., Lacour, S., Crouzier, A., David, L., Lapeyrère, V., and Schworer, G. (2018). Short life and abrupt death of PicSat, a small 3U CubeSat dreaming of exoplanet detection. In Proc. SPIE, volume 10698 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 1069821.
- Persson, S., D’Amico, S., and Harr, J. (2010). Flight results from prisma formation flying and rendezvous demonstration mission. *61st International Astronautical Congress 2010, IAC 2010*, 1.
- Plice, L., Galal, K., and Burns, J. O. (2017). DARE Mission Design: Low RFI Observations from a Low-Altitude Frozen Lunar Orbit. *arXiv e-prints*, page arXiv:1702.00286.
- Pong, C. M., Lim, S., Smith, M. W., Miller, D. W., Villaseñor, J. S., and Seager, S. (2010). Achieving high-precision pointing on ExoplanetSat: initial feasibility analysis. In Proc. SPIE, volume 7731 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 77311V.
- Quanz, S. P., Kammerer, J., Defrère, D., Absil, O., Glauser, A. M., and Kitzmann, D. (2018). Exoplanet science with a space-based mid-infrared nulling interferometer. In Proc. SPIE, volume 10701 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 107011I.
- Rankin, K., Stochaj, S., Shah, N., Krizmanic, J., and Naseri, A. (2018). VTXO - Virtual Telescope for X-Ray Observations. *arXiv e-prints*, page arXiv:1807.05249.
- Rinehart, S. A., Rizzo, M. J., Leisawitz, D. T., Staguhn, J. G., DiPirro, M., Mentzell, J. E., Juanola-Parramon, R., Dhabal, A., Mundy, L. G., and Moseley, S. H. (2016). The Space High Angular Resolution Probe for the Infrared (SHARP-IR). In Proc. SPIE, volume 9904 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 99042L.
- Roettenbacher, R. M., Monnier, J. D., Korhonen, H., Aarnio, A. N., Baron, F., Che, X., Harmon, R. O., Kővári, Z., Kraus, S., and Schaefer, G. H. (2016). No Sun-like dynamo on the active star ζ Andromedae from starspot asymmetry. *Nature*, 533(7602):217–220.
- Schaefer, G. H., Brummelaar, T. T., Gies, D. R., Farrington, C. D., Kloppenborg, B., Chesneau, O., Monnier, J. D., Ridgway, S. T., Scott, N., and Tallon-Bosc, I. (2014). The expanding fireball of Nova Delphini 2013. *Nature*, 515(7526):234–236.
- Shao, M. (1998). SIM: the space interferometry mission. In Reasenberg, R. D., editor, Proc. SPIE, volume 3350 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, pages 536–540.
- Shao, M., Nemati, B., and Zhai, C. (2010). Space Interferometry Mission (SIM)-Lite Status. In *EAS Publications Series*, volume 45, pages 141–142.
- Stachnik, R. V. and Gezari, D. Y. (1985). SAMSI: an orbiting spatial interferometer for micro-arcsecond astronomical observations. In Longdon, N. and Melita, O., editors, *Kilometric Optical Arrays in Space*, volume 226 of *ESA Special Publication*, pages 35–42.
- Welle, R., Janson, S., Rowen, D., and Rose, T. (2018). CubeSat-Scale High-Speed Laser Downlinks. In *Proceedings of the 13th Reinventing Space Conference*, page 7.

Wild, W. and Helmich, F. P. (2008). Far-infrared heterodyne interferometry from space. In Proc. SPIE, volume 7020 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 70201N.