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LINC NIRVANA at LBT: Final Preparations for First Light

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ABSTRACT

LINC-NIRVANA is an innovative, high-resolution near-infrared imager for the Large Binocular Telescope. Its Multi-Conjugate Adaptive Optics system uses natural guide-stars and provides high sky coverage for single-eye, binocular, and eventually, interferometric observations. We report on final lab integration and system level testing, as well as technical and logistical challenges of shipping and installing a large, delicate, complex instrument. LINC-NIRVANA is currently at LBT undergoing final alignment and tests before First Light late this fall. Managing the transition to operations involves the interactions between telescope alignment and calibration, commissioning of the instrument, and executing the Early Science plan.

Keywords: near-infrared, imaging, multi-conjugate, adaptive optics, interferometry, Fizeau, LBT

1. INTRODUCTION

LINC-NIRVANA (LN) has finally reached its home, the Large Binocular Telescope (LBT), after more than ten years of design, development, construction and testing at the four collaboration institutes in Germany and Italy. LN is a complex instrument, comprising a large cryostat, 4 wavefront sensors, over 2000 deformable mirror actuators, 8 science-grade detector systems (2 infrared, 6 visible), over 250 individual lenses and mirrors, 133 motors, and almost 1000 individual electronic cables. Integrating and testing such a system is a difficult enough endeavor in the laboratory; doing so in the environment of a working observatory increases the challenge. Over the last two years, LINC-NIRVANA underwent this integration and testing process in the labs in Heidelberg and on Mt. Graham (as well as a complex and difficult transport), and it is now ready to be mounted on the telescope for science operations.

2. FINAL LAB INTEGRATION AND INSTRUMENT-LEVEL TESTS

LINC-NIRVANA was constructed and assembled in a hierarchical manner, with individual sub-systems completed at collaboration partner institutes, followed by delivery to Heidelberg for assembly into the half-dozen or so separate opto-mechanical systems. Final instrument-level integration and testing took place in a large (8x8x13m) hall at MPIA during late 2014 and early 2015.

These activities included overall optical alignment, an initial report of which appears in Moreno-Ventas et al. (2014) and Bizenberger et al. (2014). At the end of this process, the total RMS wavefront error for the approximately 30 optical surfaces between the input focus and the High-layer Wavefront Sensors was less than 55 nm for both arms of the instrument. The optical path to the science focus involves fewer elements, and the delivered image quality was even better.

Given the size (5.7 x 4.1 x 4.5 meters) and weight (9.8 metric tonnes) of LINC-NIRVANA, flexure can be a serious issue. In order to assess its impact and develop mitigation strategies, we executed an extensive flexure testing campaign, tipping the instrument using a large hydraulic ram and assessing the performance as a function of angle (Figure 1). A number of components exhibited flexure effects at a level that needs correction using lookup tables.

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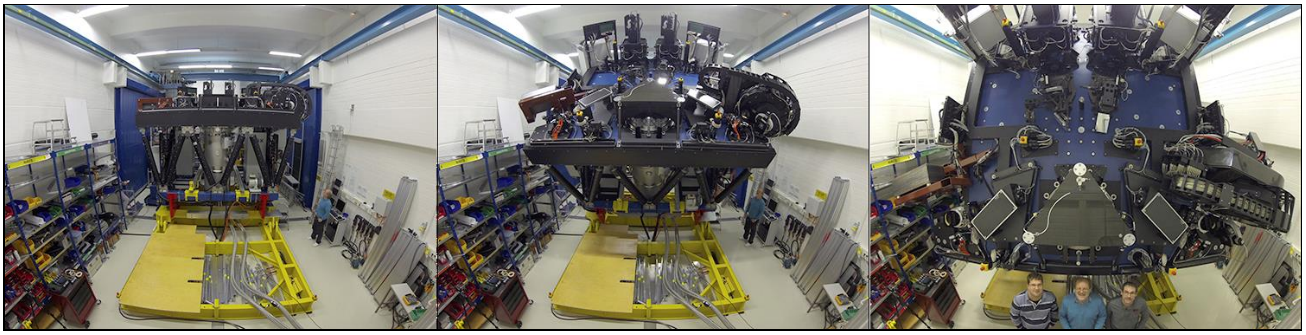

Figure 1. Flexure testing the populated LINC-NIRVANA optical bench. A large hydraulic ram tips the 10-tonne instrument from zenith to horizon, allowing assessment and calibration of flexure effects. Note the LN team members for scale.

In order to provide diffraction limited imagery over a wide field of view, LN exploits the technique of Multi-Conjugate Adaptive Optics (MCAO), in which two or more deformable mirrors (DM) are conjugated to different altitudes. In the case of LN, we correct two altitudes, the ground layer and a high layer 7.1 km above the telescope. LN measures the low-level turbulence with Ground-layer Wavefront Sensors (GWS) and corrects it with the 672-actuator LBT facility adaptive secondary mirrors. A pair of High-layer Wavefront Sensors (HWS), one per eye, measures the 7.1 km turbulence and drives commercial Xinetics DMs with 349 actuators each. Herbst *et al.* (2016, 2010) provide a complete description of the LN optical path.

These two AO control loops run sequentially. Because it requires the LBT adaptive secondaries, the ground-layer loop cannot be tested in the lab. To address this, we executed the Pathfinder experiment at the LBT in 2013. This involved bringing one of our GWS units to the telescope, along with associated hardware and software, for daytime and eventually, nighttime testing on sky. Herbst *et al.* (2014) report further on the Pathfinder experiment. During the final instrument-level testing in Heidelberg in early 2015, we calibrated and tested the high-layer loop and Xinetics DM using synthetic disturbance functions. Santhakumari *et al.* (this conference) report on the results of these tests.

3. PAE AND TRANSPORT TO MOUNT GRAHAM

The integration and instrument-level testing phase culminated with Preliminary Acceptance Europe (PAE), a mandated review held in early May 2015. LINC-NIRVANA passed PAE (with actions), triggering the next phase of the project: disassembly and shipping to the mountaintop site in Arizona. The logistics of this operation were complex for a number of reasons. First, the main optical bench assembly was fully cabled and tested. LINC-NIRVANA uses almost a thousand cables (and therefore two thousand connectors). Taking the bench apart and reassembling it at the telescope would have added considerable time and risk to the process. The bench is also too large to transport in cargo aircraft, so a sea journey was the only option. Of course, ocean transport brings its own risks, and the requirement of a custom large shipping container did not mean that this choice was much less expensive. Getting the packaged bench to a barge on the nearby Neckar river was also a challenge, due to narrow winding roads, on-street parking, and occasional bottlenecks in the surrounding villages (Figure 5).

In the end, the LINC-NIRVANA shipment comprised the large custom crate and nine standard shipping containers, a total of 37 metric tonnes. In mid-September 2015, the crate traveled down the Neckar by barge to Bremerhaven, while the containers left MPIA by truck to the same port. From there, the shipment traveled to Port Hueneme, California via the Panama Canal, and then onward by truck to the Mt. Graham base camp, arriving in late October. From base camp, the crate and containers were staged to the summit during re-integration, due to restricted storage space in the LBT high bay.

Figure 2. Some of the logistical challenges associated with transporting a large instrument through a population center. Due to its size, the LN crate required a night transport with police escort to close roads as needed (left). Some of the older surrounding villages provided interesting bottlenecks where the clearance around the crate was only a few cm (right).

4. RE-INTEGRATION AND INSTALLATION ON THE TELESCOPE

Starting in November 2015, activity shifted to the LBT high bay and mountain lab. Re-integrating LINC-NIRVANA was a complex logistical exercise. Not only was there a very large number of tasks to execute, but also the choreography of team members with different areas of expertise proved challenging. In addition, all of this activity had to be coordinated with the required mountain staff, such as crane and forklift operators, in the context of an active, operating observatory. Finally, the building permit for the LBT severely limits accommodation. With observatory staff, other instrument teams, and observers, it was difficult to place more than four or five LN team members on site at a time.

In the end, we divided the re-integration into eleven separate campaigns spanning 14 months between summer 2015 and autumn 2016, a total of more than 600 person-days of effort at the observatory (Table 1). The campaigns began with dismounting the Pathfinder experiment from the telescope to make way for LINC-NIRVANA, and will conclude in September 2016 with final installation of the aligned instrument on the telescope. At the time of this SPIE conference in June 2016, we will have completed 9 campaigns (indeed, some team members could not attend the Edinburgh conference, as they were still engaged in I-10. Note also that the team managed to complete the planned I-7 activities during I-5, reducing the total number of actual campaigns to ten.

Table 1: LINC-NIRVANA re-integration planning

Run	Activity	Personnel	Dates
I-1	Dismounting Pathfinder, GWS refurbishment	2	11-17 Jun 2015
I-2	Inspection of shipment, unpacking, test installation on telescope	8	8-25 Nov 2015
I-3	GWS internal alignment, computer environment installation	4+4	12-28 Jan 2016
I-4	Bench and cryostat integration	5	23 Feb - 4 Mar 2016
I-5	Warm optics alignment (left eye)	3	1-16 Mar 2016
I-6	HWS alignment (both eyes)	4	12-26 Apr 2016
I-7	Warm optics alignment (right eye) - obsoleted	-	-
I-8	Optimization and high-layer loop work (both eyes)	4	26 May-9 Jun 2016
I-9	GWS and annular mirror alignment (both eyes)	5	4-11 May 2016
I-10	Cryostat and overall instrument verification	5	10-21 Jun 2016
I-11	Final installation on telescope	8	16-28 Sep 2016

5. TEST INSTALLATION ON THE TELESCOPE

The physical envelope of LINC-NIRVANA strains the dimensions of a number aspects of the LBT. For example, installation of the instrument requires that the enclosure crane operate at the limit of its range, and direct lowering of LN onto the instrument platform is impossible due to its size and mechanical obstructions of the telescope. LINC-NIRVANA is too tall to crane over the telescope, and passage over the primary mirrors is not possible. The team therefore had to develop a careful choreography, in which the telescope tips to horizon while LN moves up and over. Both the telescope and crane must then carefully move in synchrony back to the zenith-pointing configuration to bring the instrument to its mounting location. In addition, the scheme for installing and removing the science channel cryostat (independent of the full instrument) required substantial modification of the LBT visitor gallery and other human passageways.

Perhaps most challenging is the fact that all hardware must be craned into the enclosure through a 10m x 4m hatch, which opens onto the high bay below. While the long dimension certainly suffices, LN's clearance on the hatch width is approximately 10 mm on each side. Thus, installation of LINC-NIRVANA involves raising it approximately 25 m from the high bay floor and then passing through an aperture only slightly wider than the instrument itself. Any deviation from strictly vertical suspension and motion, or any wind-induced sway of the enclosure-mounted crane hook could cause serious problems. A final, related complication is the fact that the mechanical structure of LN requires it to be suspended from its lowest point. This necessitates a custom lifting traverse, but this traverse cannot in any way increase the width of the payload.

As a result of all this, the LN team, working in collaboration with the observatory, decided to perform a test flight and installation of the bare optical bench (i.e. no opto-mechanics) during the first post-delivery re-integration campaign (I-2, see Table 1). This full-day operation began with careful balancing of the load on the crane, so that LN hung exactly vertical and square. The crane operator then worked with multiple assistants handling tag lines to slowly maneuver the instrument up to the hatch. Passage of the ~6m high load through the thinnest part of the hatch took approximately ten minutes. Thereafter, the crane-telescope "dance" took place, bringing LINC-NIRVANA to a location directly above its destination (Figure 3). A final rearward then forward jog avoided the remaining obstructions and LN landed on its mounting pads. The LN/LBT team then installed and tested the 32 large mounting nuts, removed the lifting traverse, and after re-balancing the telescope, tipped LINC-NIRVANA over to horizon for the first time in its new home. The entire procedure succeeded without a hitch, and although the potential for significant delays were built into the planning, nighttime operations began on schedule.

Two days later, the team performed a test-fit of the LINC-NIRVANA dust cover, which attaches to the telescope, not the instrument, to avoid transmission of wind-induced vibrations to the optics. This, too, was successful. Two days later, both the cover and instrument were dismounted and returned to the high bay. The team then rolled LINC-NIRVANA into the mountain lab for its lengthy re-integration and alignment phase.

6. PRE-COMMISSIONING, COMMISSIONING, AND EARLY SCIENCE

Successful installation of LINC-NIRVANA on the telescope in fall 2016 does not signify readiness to go on sky. Our alignment procedure in the mountain lab results in an instrument that is internally aligned – that is, all of the opto-mechanics are positioned correctly with respect to each other and with respect to our external reference points on the bench. These points are the two telescope foci and a third location defined by a stable rod mounted to the bench. These 3 locations accommodate ball nests for laser tracker targets, and during the I-11 installation campaign, we will use these targets to place the instrument at the mechanically correct location. LINC-NIRVANA has custom mounting plates that allow fine adjustment in X-Y before tightening. Vertical adjustment requires the installation of shim plates. Our anticipated uncertainty in bolting, *ca.* 1 mm, is within the capture range of the mechanical motion of the bulk optics of the telescope.

6.1 Pre-Commissioning

With the instrument properly positioned to within a millimeter of the correct location, we will execute a pre-commissioning campaign in November 2016 to bring the primary, secondary, and tertiary mirrors of LBT into alignment with our bench. Encoders on all motion axes allow us to return the telescope to this configuration during future commissioning and science runs.

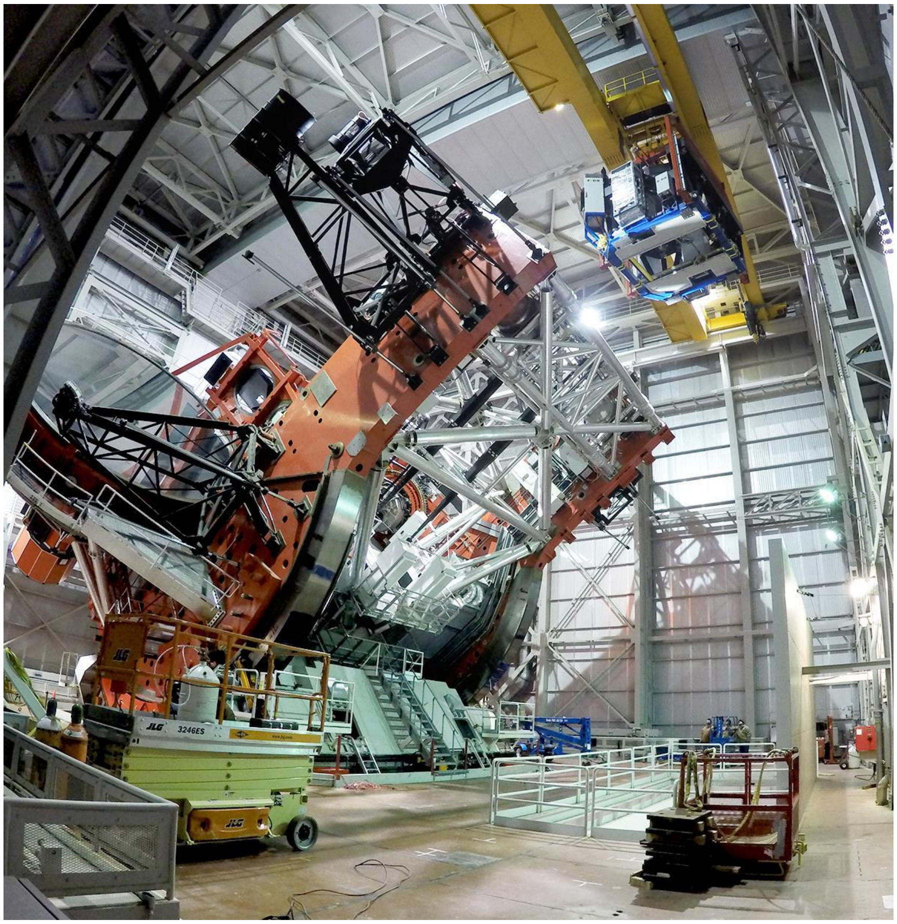

Figure 3. LINC-NIRVANA, suspended from the crane high above the dome floor to the upper right, has just emerged from the enclosure hatch at bottom center. The instrument-telescope dance is about to begin, allowing LN to fly over the midline of the LBT to its final mounting location on the bent-Gregorian instrument platform.

6.2 Commissioning

The commissioning of an instrument as complex as LINC-NIRVANA presents its own unique challenges. For example, in its early implementation, it will operate in “single-eye” mode, but we will want to ensure that the early commissioning activities can be carried over into the dual-eye, beam-combined configuration, both incoherent and coherent. In addition, the instrument hosts eight science-grade detector systems and 40 different control systems. The commissioning plan thus adopts a stepwise approach, with the idea that early science requiring only certain modes can be interspersed with on-sky characterization and testing. It also attempts as much as possible to use daytime measurements. Although these will typically require dark conditions with the telescope positioned at a certain angle, they do not consume valuable nighttime hours.

We have also adopted the strategy of splitting commissioning nights with regularly scheduled observatory science. This is partially a reaction to the requirement of small commissioning teams imposed by the limited on-site accommodation. The more compelling reason, however, is the recognition that, given the instrument’s complexity, we will inevitably confront roadblocks that will stop us for several hours. Being able to hand the telescope over on short notice to science minimizes the impact of such events.

The commissioning plan exists as a living, wiki-based document, and is being continuously refined. It currently fills approximately 250 usable nighttime hours, or 30 nights. Given competing demands at the LBT, we have reached an agreement to spread this activity over four semesters, interspersed, as mentioned above, with the Early Science plan.

6.3 Early Science

As the previous section emphasizes, we recognize that LINC-NIRVANA will not immediately work in all modes at full performance. Bringing the instrument into regular operation will also require a substantial engineering team at the telescope and regular interruptions to address technical issues. And, as mentioned above, we plan to intersperse commissioning activities with early science as much as possible. This environment is not one typically encountered by astronomers visiting the observatory.

As a result, we have developed a diverse, early science program that will be executed by the LINC-NIRVANA team before the instrument is offered to the wider community. It includes six programs which can exploit LN's unique capabilities to produce a high visibility result with a modest investment in observing time (typically 10-20 hours). Moreover, the call for proposals demanded a local "champion" willing to work with the LN team in a flexible way. The science cases have been developed to the level of having realistic exposure time estimates, actual on-sky targets, and suitable AO reference asterisms. As a final requirement, the programs span the full right-ascension range, so that there should be suitable targets during every commissioning run.

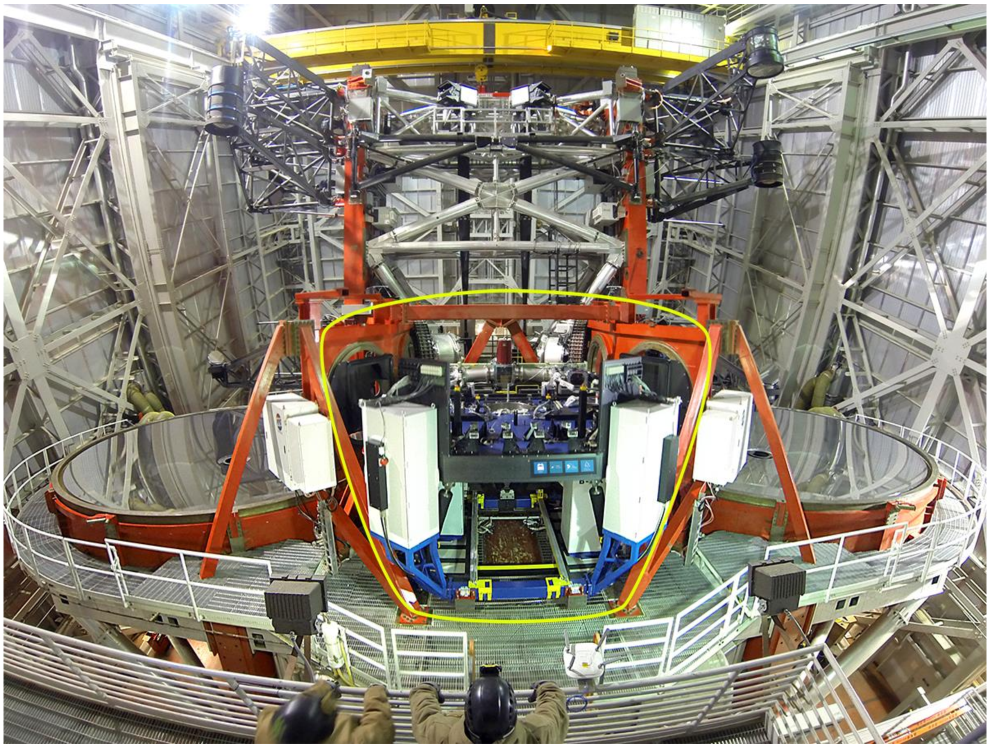

Figure 4. LINC-NIRVANA (inside yellow line) installed at the rear, shared, bent Gregorian focus of the LBT.

7. THE FUTURE

At delivery in autumn 2015, LINC-NIRVANA supported single-eye MCAO imaging with either the left or right telescope of the LBT. This permits diffraction-limited imagery in the near-infrared with very uniform image quality and high sky coverage. Nevertheless, there are clear ways forward to increase the scientific return of the instrument.

The first step will be to bring dual-eye, incoherent imagery online. This will effectively double the integration time of a particular LN observation. All of the hardware is in place and tested for this mode, and the only remaining step is to ensure overlap of the delivered images from the two sides. This means matching the pointing direction, field rotation, and image scale. The first of these should be straightforward, as the adaptive secondary mirrors lie in the pupil plane; a simple adjustment of tip-tilt will align the two pointing directions. Matching the image scale should come as a matter of course. In an adaptive telescope such as LBT, the exact image scale for a natural-guide-star MCAO system is set by the mechanical accuracy of the star probes in the wavefront sensor. In other words, placing the probes at a certain location will bend the deformable mirrors in such a way as to center the stars on the probes. The image scale is then determined by how well the stages do their job, and modern hardware is more than capable of meeting our specifications. The final piece of the puzzle, image rotation, is more challenging to deal with. It can arise if there is an asymmetry in the placement of LINC-NIRVANA between the two primary mirrors, either spatially or in rotation. The use of targets and the laser tracker should eliminate this possibility, but there are a couple of ways of correcting minor differential rotation, which involve displacing or rotating the instrument slightly.

A second obvious upgrade step involves the image scale, which is currently 5 mas per pixel in order to Nyquist sample the interferometric point spread function. Clearly, for single-eye modes such as MCAO, this oversamples the field of view, and we would prefer a scale closer to 15-20 mas per pixel. Changing the pixel scale would involve a swap of the final camera optics within the cryostat, changing the focal ratio from the current f/88 to approximately f/22. With beam diameters of ~130mm and 2 meters of linear track available within the cryostat, constructing and installing such optics should not present a challenge. Indeed, we have done some preliminary design work (Figure 5), and in early 2016, we submitted a proposal to the LBT Scientific Advisory Committee to do the upgrade. The proposal was greeted favourably, and we are currently examining funding and collaboration options to accomplish this on a fast track.

LINC-NIRVANA was designed and built to do interferometry. Again, all of the necessary hardware has been built, tested, and installed to accomplish this. There are several remaining tasks before we can attempt this mode on sky, however. First, the fringe tracker needs additional testing and integration work to bring it into the overall LN environment. More importantly, the signal chain between fringe tracking detector and the down-folding delay line needs both software and testing effort. We are working with our partners and the observatory to find resources to accomplish this.

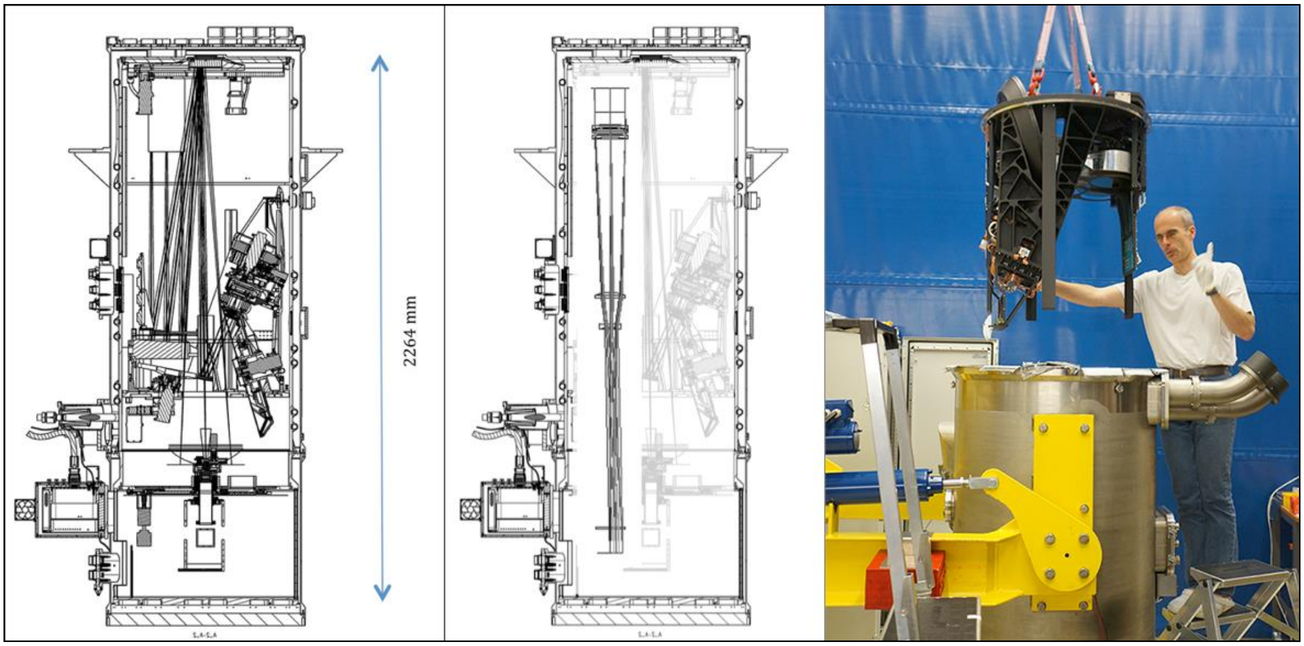

Figure 5. Upgrading the cryostat optics for wide-field operation. The current optics (left panel) fill the 2.25 meter long volume of the cryostat. A straightforward, purely transmissive optical system (center panel) can deliver a 42” field to the existing Hawaii-2 array and even support an 84” field on a Hawaii-4. Exchanging the optics is a single-day operation, as all components are mounted on an internally calibrated backbone, which can be removed as a unit (right panel).

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