On converting the Blanco telescope to a general purpose survey facility.

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Abstract

There exists a conceptual design for a highly-multiplexed, fiber-fed, prime focus spectrograph for Blanco using DECam's corrector and hexapod. Since that design was produced, a number of similar projects have advanced, will soon be deployed, and can inform choices for plans on the Blanco. If the Blanco is to carry such an instrument, some upgrades to DECam will be necessary. Those upgrades may be usefully applied independently of any new instrument.

The Blanco telescope is an excellent – indeed the only – platform of 4m and bigger, for wide field study of the southern skies and readily available to the NOAO community. The work done prior to and during the installation of DECam has made it a highly reliable, optically stable, and realistically state-of-the-art facility, keeping it maximally efficient and productive despite its 44 years of operation. Combined with DECam, time on the Blanco telescope is sought after at a level which can be compared with many larger and more modern facilities. In the first half of 2017 the productivity (in terms of papers published) of the telescope, even before DES observations are completed and well before all the data have been reduced, was approximately equal to the sum of the other three 4-m telescopes in NOAO stable (SOAR, WYNN, Mayall). The Blanco is certainly a valuable platform for science, especially in wide fields and for surveys, and its place in the Decadal Survey merits careful examination.

If the community seeks to build a new, 8-m class telescope dedicated to wide field spectroscopy surveys, an intermediate step with some merit would be to build an intermediate platform on an existing telescope. This could provide stepping-stone benefits similar to those DECam has provided to LSST, and Blanco is the obvious host facility. Nevertheless, few indeed would argue that DECam will be ready for retirement any time soon. Instead, it would be better to build a large survey spectrograph to be used alongside DECam, ensuring a smooth and productive transition from a primarily imaging facility to one where spectroscopy becomes the principal use as the imaging side is increasingly dominated by LSST.

While DECam was being mounted on the Blanco telescope in 2012, a subset of the DES collaboration held a meeting to discuss options for later conversion of DECam to a spectroscopic facility. The meeting yielded a conceptual design called DESpec[1], and using a fiber drive system called MOHAWK[2].

The DESpec program proposed to use the first four lenses of the DECam corrector (the 5th and last lens is the imager window) and introduced two additional lenses to produce 0.25" to 0.44" RMS spot sizes from center to edge with a peak non-telecentricity of 0.45°. The focal surface has an 8 m radius of curvature and the corrector produces a focal ratio of f/2.9, appropriate for injection into a fiber. They also consider an atmospheric dispersion corrector which would reside in the current location of the DECam filter carriage and shutter units, which are removable. The favored fiber positioner technology was the tilting-spine, or Echidna (first described in [3]), in which the fiber is mounted on a long thin rod, which is tilted using a piezoelectric actuator mounted on a ball-bearing pivot. 4000 fibers can then cover a 450 mm diameter field with a pitch of 6.75 mm, a reconfiguration time of ~15 s, and a placement precision of 7 µm at the focal plane. Approximately 6% losses were anticipated due to focal ratio degradation at the tip of the fiber due to a maximum telecentricity error of 1.55°. The project proposed two spectrograph designs: single and double-armed. The single-armed design is essentially a copy of the HETDEX/VIRUS spectrographs with wavelength coverage λ = 550 – 950 nm and resolution δλ = 0.263 nm, and the preferred, double-armed design covered bands λ = 480 – 780 nm and λ = 750 – 1050 nm at resolution δλ = 0.228 nm. The construction cost was estimated at $40M. The project did not mature beyond this concept, but a lot of the fundamental thinking was done.

Since 2012, of course, six years have elapsed and the landscape has evolved somewhat. For example, the titling-spine technology has progressed [4] and a number of technologically related instrument projects have advanced considerably in construction and towards deployment. Tabulated in the appendix, I provide an overview of currently existing and planned survey spectrographs in which light-collecting fibers are moved around the focal plane using various types of robot.

Four robot technologies are used. Of existing, operating instruments, all but one use the tried-and-tested robot & plate, and numerous other instruments (e.g. NOAO's Hydra[5]), now retired, have worked similarly. In this case, the robot, typically riding on an XY stage, picks up fiber heads incorporating magnets and places them as required on a magnetic plate which is positioned at the focal plane. Each field is time-consuming to configure since typically only one fiber is placed at a time, although at least 2dF, WEAVE and BOSS use multiple plates to allow observations with one in parallel with configuring the other. This technology appears to be limited to ~1000 fibers at most.

The three newer fiber-positioning technologies are the aforementioned tilting spines, the theta-phi arrangement of rotating posts (first described in [6]) and Starbugs (first described in [7]).

The tilting spines operate by mounting the fiber on a rod, the spine, and sweeping it in RA & Dec using piezoelectric actuators. The rotating posts carry the fiber from site to site via two pillars with offset axes driven by stepper motors. Starbugs are small cylinders carrying the fiber at the center and containing concentric piezoelectric feet; these adhere to a glass plate (through which the fibers look) by means of an applied vacuum and can be made to walk across that plate via a stick-slip mechanism as varying voltages are applied to the feet.

Typically, tilting spines are spaced the closest, 6 to 9 mm and allow the smallest fiber head separation (~1 mm), as such they may be first choice for the more cramped focal planes. Starbugs can move fibers to within 9mm of each other, but are restricted in overall density on the focal plane by their need to navigate around one another and the generally larger pitch of their supporting electronics. Rotating posts range in pitch from 8 to 25 mm, and allow fiber proximities down to ~3 mm. In all cases care must be taken to avoid fiber collisions. The planned tilting spines instruments have up to 4000 fibers, rotating post instruments have up to 5000 fibers, and Starbug instruments have up to 1000 independent actuators.

Since both tilting spines and Starbugs use piezoelectrics they require the routing of relatively high voltages (100-200V) near the focal plane, which is a potential disadvantage. Tilting spines have an additional disadvantage that away from their centered position, they will no longer be telecentric as the spine becomes increasingly inclined to the optical axis. This will reduce the efficiency of the fiber by a few percent. The deficiency is ameliorated by using longer spines. In the harsh environment normal at a telescope, moving parts are among the greatest source of failure; given that the number of moving parts in a rotating post design is larger than the others, they might be expected to fail more frequently.

To date, Starbugs have only been used as prototypes and only two instruments using rotating post (LAMOST) and tilting spine (FMOS) technologies have actually been deployed; the rest are still in development. Both of these instruments have had their issues, and FMOS is now retired.

FMOS was mounted on Subaru such that the field would rotate against the fibers as observations progressed, limiting time on a single field to 30 minutes before a reconfiguration was required [8]. Given that reconfiguration took up to 700sec[1], one can safely conclude that on-sky efficiency was somewhat poor. Moreover, changing telescope focus with varying temperature also caused target displacements in the instrument's focal plane. Clearly, proper interfacing with the telescope is a critical consideration, and perhaps it speaks volumes that Subaru have moved to rotating posts for their next such instrument, SuMIRe/PFS.

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[1] Configuration was iterative with feedback provided by a camera to view the back-illuminated fibers at each step. Since the camera could view only a portion of the FPA it was mounted on a stage and scanned. One pass took 100sec, and 7 passes were required to reach the required precision.

For its part, LAMOST seems to have suffered from a significant level of errors in the positioning of fibers, with as many as 8% of fibers being placed 7” or more away from their intended positions [9], and a significant number of collisions [10], at the 3-4% level, occurring between the actuators as they move into position. There is also mention of actuator mortality through aging, although I have not found a statement of how severe is the problem. It may be noted that the LAMOST program are developing a new, smaller actuator design to allow a 25% increase in the number of fibers in the instrument, and presumably replacing the currently installed actuators [11].

Unanticipated failures are inevitably the lot of those pioneering new technologies and we should applaud them for doing so, so that the rest of us may learn for our own attempts.

UPGRADING BLANCO+DECAM

Similarly, since 2012, the landscape at CTIO has evolved somewhat. 6 years of experience operating DECam on the Blanco has taught us a great deal. If the telescope is to be host to a prime-focus, highly-multiplexed spectrograph, a number of issues will have to be addressed.

Of course, the new spectrograph and DECam could not be available simultaneously, and as with any multi-purpose telescope, some way to switch between them, quickly and efficiently, is desired. Given instruments at prime focus, covering a field of view two degree across, this is no small challenge. Fortunately, the DECam development team had sufficient foresight to avoid designing the imager in such a way that it could not be removed from the telescope and thus left the potential to build further instruments which might use the same corrector and hexapod. That said, DECam was not designed to make such an operation easy. In particular, the cooling chain, involving a large tank of LN_2 off the telescope, a cryogenic pump, a quantity of heavy, vacuum-jacketed piping, and running at 100 PSI, would not be trivial to warm up, disconnect, reconnect, and cool down. Even without removing the imager from the telescope, we know from experience that the warmup and cooldown procedures take an absolute minimum of 4 days.

The cooling chain as installed is the result of a conservative design philosophy in which a high-capacity cooling system would allow for less stringent demands on the thermal efficiency of the dewar. In hindsight and considering Parkinson’s Law, it was perhaps predictable that the design as built uses all of the available power of the cooling system. In practice, approximately half of that capacity is expended in merely delivering liquid nitrogen to the dewar. Furthermore, approximately half of the cooling power available at the dewar is expended by heating of the focal plane array in order to close the temperature control loop on the CCDs. This is hardly optimal design.

Moreover, the cooling system is by far the most troublesome component in the DECam system, being directly responsible for the greatest loss of telescope time due to system failure during DECam’s life so far. Most of this is traceable to the liquid nitrogen pump inside the dewar off the telescope. The pump is run continuously, and is unlubricated. It devours its own bearings. The original design called for an MTBF of two years. After many cycles of design and redesign, we have converged on an 8 month cycle between pump replacements, and even then we still lose time to failures in which the observing schedule is interrupted for a minimum of four days and typically up to a week while we warm up, replace the pump, and cool down again. Given that telescope time costs approximately $17k per night, this is no small loss, never mind the inconvenience to the observers and the progress of their science. The pump has failed while in use twice since DECam saw first light, and been programmatically replaced 7 times. Allowing 6 days per instance, this is a total loss of 54 nights or $918,000 for telescope time alone.

Significant further resources have also been expended in leak-proofing the vacuum-jacketed lines which carry the high pressure liquid/gaseous nitrogen. Now installed are the third iteration of the first stages of both of the lines coming from and returning to the main tank (7r and 7s, to the cognoscenti), and the second iteration of the last stages of both lines (1r and 1s). It is unrealistic to suppose that the leaks will ever be definitively and permanently sealed.

There are some means by which the situation might be ameliorated, and simultaneously to facilitate easier removal and reinstallation of the imager, encouraging alternative uses of the corrector. That is to say, instrument changes can be made quicker and easier, and running DECam itself can be made easier, cheaper, and more reliable. The cooling system might be replaced entirely, most probably with a direct cooling of the focal plane, at prime focus, using cryocoolers. This was not deeply explored in the original design because it was believed that it would require three cryocooler heads mounted on the back of the dewar where there was insufficient space. But that was with a dewar which was not optimized for thermal efficiency with little insulation and a high-bandwidth cooling control loop.

Thermal radiation losses to the dewar window are approximately 50W. Another 50W is lost to keeping the dewar electronics cold. Finally, just over 100W is lost to heating the over-cooled focal plane. A lower-bandwidth cooling control loop can reduce the latter number considerably. Careful redesign inside the dewar should identify ways to reduce heat dissipation from the electronics and improve insulation so as to reduce those losses as well. For comparison, the focal plane of the ZTF is cooled using two PT-16 charged Polycold Joule Thompson coolers which can extract approximately 24 W of heat at -100 °C, each. While Smith, et al. [12] claimed the final design had “almost a factor-of-two cooling power margin”, reality proved a little more demanding [13], but nevertheless there is adequate cooling power for a focal plane ~6% bigger than DECam’s.[2,3]

Besides the time lost to pump replacements and otherwise servicing the LN_2 system, the electricity required to run the current DECam cooling system costs around $40k/year (cryocoolers: 2x5 kW + 20 kW glycol) half of which is used solely to maintain the LN_2 flow. Clearly, on these bases alone, there is an argument for an engineering study on what it would take to replace DECam’s LN_2 cooling system with cryocoolers. But there are other potential benefits:

- It would remove considerable weight from the telescope (~several tons), both as the weight of the heavy vacuum-jacketed LN_2 lines, and as counterweight on the back end.
- Connecting and disconnecting crycoolers is considerably easier than 100 PSI, vacuum-jacketed LN_2 lines.
- The space behind the DECam dewar becomes considerably less crowded.
- Given the much reduced thermal capacity of the whole system, warmup becomes faster. Furthermore, keeping the in-dewar LN_2 circulation system leaves the possibility of accelerating cooldown, even with a lower bandwidth cooling system, by running LN_2 through it while the telescope is at the northwest service station.
- Which all means, too, that it becomes easier to dismount and remount the DECam imager on its corrector.

A dismountable fiber-feed head on the DECam corrector will inevitably need to be removed from the telescope entirely when not in use. Therefore a break in the fibers is a necessary design component. As seen in the appendix other projects have adopted this approach, in the case of SuMIRe with two such breaks. The designers typically anticipate light losses at the level of a few percent.

Variations on the design of the spectrograph might be considered beyond merely a large number of fibers feeding a bank of identical spectrographs. For example, a single, fixed fiber could be selected to feed a stabilized high-resolution spectrograph as in HARPS on the La Silla 3.6-m, providing a platform for radial velocity studies not currently available to the NOAO community. Unfortunately Blanco’s image quality is unlikely to be adequate for the purposes of integral-field spectroscopy, there being other, better platforms already within the community’s reach. In either case, there is no shortage of space within the Blanco building for locating spectrographs.

Finally, considering the upgrade path, it would make be most efficient to build the spectrograph first, install it on the Blanco, and only then proceed with upgrades to the DECam imager. This would likely mean a long initial season for the spectrograph while previously planned upgrades are applied to DECam. It is probable that the DECam dewar would need to be partially redesigned, most likely at least the rear plate would be replaced.

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[2] ZTF’s cooling is assisted by using the field flatteners as thermally floating radiation shields. DECam does not employ field flatteners, but the principle argument against introducing a thermally isolated, optically neutral plate between DECam’s FPA and the dewar window is likely to be the photon losses which can be minimized with suitable coatings.

[3] DECam: $(62 + 12/2)$ CCDs × 1887 mm^2/CCD = 128,345 mm^2, ZTF: 16 CCDs × 8515 mm^2/CCD = 136,249 mm^2

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APPENDIX: EXISTING AND PLANNED SPECTROSCOPIC SURVEY INSTRUMENTS

The following tables summarize parameters of 19 instruments, existing and planned, which utilize robots to position large numbers of fibers in a telescope’s focal plane, which then carry the light from celestial sources to off-telescope spectrographs. To the best of my ability, the tables are complete to the extent possible using publicly available websites and journal articles. Retired instruments are not included with the exception of Subaru’s FMOS as it is the only existing instrument using a fiber-positioning technology more recent than the magnetic plate + robot.

Notes on the tables:

- A “→” symbol in the “beam speed at fiber head” column indicates a change in beam speed at the focal plane using foreoptics on the fiber.
- Entries which remain uncertain are marked with “?”.
- Cells for which I have located no data remain blank, although some blank cells are for values not relevant to the technology used.

Notes on individual cells (in superscript):

1. "In the NIR wavelength range of 0.9-1.8µm, the atmospheric dispersion is 0."1 and 0.3" at zenith distance of 30 and 60 degrees, respectively." [14]
2. 92 small IFUs of 7 fibers each.
3. Square format, 3.5 arcmin on a side.
4. A “→” in the “Beam speed at fiber head” column implies the presence of foreoptics on each fiber to convert the beam speed.

Instrument	Telescope	Planned for ops	Positioner technology	ADC?	Max zenith distance deg	Fiber has break	Fiber length m	#fibers	Primary references
FMOS-Echidna / IRS1&2	Subaru (8m)	Decommissioned 2016	Tilting spines (Echidna)	No[1]		Yes	62 + 7.6	400	[14][15][16][17]
BOSS	Sloan (2.5m)	In use	Manual plug plate					1000	[18]
2df / AAOmega	AAT (4m)	In use	Magnetic plate & robot	Yes	60	No	38	392	[19]
AF2	WHT (4m)	In use	Magnetic plate & robot	Yes		Yes	26	150	[20]
LAMOST	LAMOST (5.6m)	In use	Rotating posts				32.5	4000	[21]
Hectospec	MMT (6.5m, Cass)	In use	Magnetic plate & robot	Yes		No?	26	300	[22]
FLAMES	VLT (8m)	In use	Magnetic plate & robot	Yes		No	55	132	[23][24][25]
TAIPAN	UK Schmidt (1.2m)	In commissioning	Starbugs	No		Yes	30	150	[26][27]
DESI	Mayall (4m)	Install 2018/19	Rotating posts	Yes	60	No	49.5	5000	[28]
WEAVE	WHT (4m)	SciOps end 2019	Magnetic plate & robot	Yes	65	No	32	960, 940	[29][30]
AESOP / 4MOST	VISTA (4m, Cass)	SciOps in 2021	Tilting spines (Echidna)	Yes	55	Yes	18.5+1.5	1624 (LR) + 812 (HR)	[31][32]
MEGARA	GTC (10.4m, folded Cass)	SciOps imminent	Rotating posts			No	40	644[2]	[33][34]
SuMIRe / PFS	Subaru (8m)	SciOps in 2020	Rotating posts	Yes		Two	65	2400	[35][36]
MOONS	VLT (8m)	SciOps in 2020	Rotating posts	Yes			10	~1000	[37][38][39]
MANIFEST	GMT (24.5m)	TAIPAN is the protoype	Starbugs	Yes		Yes?	5 & 25	"up to 1000", ~5000	[40][41][42]
DESpec / MOHAWK	Blanco (4m)	Discussed 2012, stalled	Tilting spines (Echidna)	Yes	60	Yes	30	4000	[1][2]
MOSAIC	E-ELT	Early development	Unspecified					200 (Opt, small IFUs), 100 (IR)	[43][44]
SDSS-V	APO (2.5m), LCO (2.5m)	In development	Rotating posts	No		Yes		(500 (Opt) + 300 (IR))×2	[45][46]
MSE	CFHT (11.25m)	In development	Tilting spines (Sphinx)	Yes	60	No	30, 50	3249 (+ 1083HR)	[47][48]

Instrument	Techno-logy	FOV diameter arcmin	Beam speed at fiber head	Plate scale at fiber arcsec/ mm	Positi-oner pitch mm	Fiber patrol radius mm	Positioner accuracy arcsec	Minimum fiber head separation mm	Fiber diameter microns	Wavelength coverage nm	Resolution
FMOS / IRS1&2	Spines	30	2	12.00	7	7.00	0.2	1	100	900-1800	600, 2200
BOSS	Plug plate	180	5?						2"	360-1000	1560-2650
2df / AAOmega	Plate +robot	120	3.4-3.5	15			0.3	2	140	370-850, 470-950	1,000-10,000
AF2	Plate +robot	60	2.8	16			0.4	1.6	90	350-1100	1000-4000, 60,000
LAMOST	Posts	300	5	10.3	25.6	16.5	0.4		320	370-900	1,800
Hectospec	Plate +robot	60	5.3	5.9			0.15	3.4	250	350-1000	1000-2500 & 32,000
FLAMES	Plate +robot	25	5	1.7			0.1	6	70	370-950	7,000, 20,500
TAIPAN	Starbugs	360	2.5	64	17		0.3	9	50	370-870	>2100
DESI	Posts	192	3.75	14	10.4	6	0.07		107	360-980	2000-5000
WEAVE	Plate +robot	120	2.8	17.8			<~0.2	3.4	85	366-959	3000-7500, 13000-25000
AESOP / 4MOST	Spines	150	3.28	59.4	8.8	10.5	0.17	1	85	370-950 & [392-435,516-573,610-679]	4,000-7,800, 18,500
MEGARA	Posts	3.5[3]	17→ 3	6	20.1	11.6	0.15		100	365-970	6000, 12000, 18700
SuMIRe / PFS	Posts	82.8	→2.8	10.3-11.3	8	4.75	0.06	3	127	380-1260	2300-4300
MOONS	Posts	12	15→ 3.65	2	25	25	0.04	5	150	600-1800	4000-6000
MANIFEST	Starbugs	20	8→ 3	1	50		0.02	8	2500	320-1600	1000-6000,& 9,000-108,000
DESpec / MOHAWK	Spines	135	2.9	18	6.75	8.1	0.18	0.5	100	480-1050	2100-4600
MOSAIC		6		0.31		98.3				450-800, 800-1800	5000, 15,000
SDSS-V	Posts	APO: 172 LCO:114	APO: 5 LCO: 7.5	APO: 16.5 LCO:19.9	22.4	7.4-22.4 annular	APO: 0.16 LCO: 0.11	5 (?)	120	360-1000, 1500-1700	2,000 (Opt) 22,000 (IR)
MSE	Spines	91.2	2	9.37	7.77	9.63	<0.1	0.75	105	360-1300, [370-460,505-630,720-900,1452-1780]	3300, 5900, (40,000)

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