Whitepaper submitted to the New York Astronomical Corporation
in response to a call for concepts for a New York State telescope

ALPACA
Advanced Liquid-mirror Probe of Astrophysics, Cosmology and Asteroids:
a low-cost, wide-field 8-meter optical survey telescope

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Executive Summary

We propose an amazingly simple yet powerful and cost-effective ground-based 8-meter survey telescope that will perform optical imaging over a wide field to a depth not envisioned by any competing project, even LSST. The strength of this concept is its design that is on the one hand based on primarily off-the-shelf and non-moving parts, but on the other hand could incorporate recently-perfected primary mirror technology which could greatly decrease the project cost. The science goals of this survey are potentially myriad, but could easily be used in refining the Type Ia supernova standard-candle relation which served as the basis for the discovery of dark energy and will be necessary for more refined future measurements of the higher moments defining the nature of that dark energy. Other projects extend from very high redshift to near-Earth asteroids, with much to be studied in between. We describe how much of the manufacture of this facility could be accomplished in New York, and we have already established an excellent site for its operation within the NSF site on Cerro Tololo. The overall project cost is surprisingly low for such an inspiringly powerful facility, so low that it might realistically find support within State government. We view this project as an excellent resource to inspire a wide range of research for New York astronomers, and describe how it could unify the State-wide community, with synergistic effect.

1. Introduction

ALPACA will be one of the largest telescopes in the world, but will cost an order of magnitude less than telescopes of similar size. This remarkable cost/ performance ratio can be achieved by concentrating on essential requirements of a general-purpose survey telescope. Since the objects being studied are ubiquitous, one is free to pick those passing overhead. Since these objects can be followed electronically by drift scanning, rather than using a mechanical mount, the mechanical structure of the telescope is greatly simplified. By pointing to the zenith, the telescope enclosure likewise has minimal requirements. The imager needs no shutter or filter wheel, again minimizing the costs and enhancing reliability. Finally, this simple mode of observation and analysis will produce large savings in data handling and analysis costs.

Figure 1: Artist's impression of the ALPACA telescope.

The great strength of ALPACA, then, is the simplicity of the telescope, instrumentation, and data products. The telescope has very few moving parts (with the exception of the rotating primary mirror). Furthermore, all detectors deliver data from the sky with 100% duty cycle so long as weather and sky conditions permit, eliminating normal interruptions for readout, hardware reconfiguration or telescope repointing. The data read out continuously in time-delay integration or "drift scan" mode (similar to the enormously successful Sloan Digital Sky Survey - SDSS); software to handle such data has already been highly developed. As discussed below, this leads to simple means for analyzing the data much more straightforward than more conventional schemes, and greatly simplifies the effort and expense of producing final data products.

2. Science capability

Within three years, ALPACA will reach a 10s limit of b ≈ 28.5, reaching the galaxy crowding limit, and consideration of further uses for the telescope will be in order. ALPACA could incorporate a multiobject spectrograph to acquire many (~30 to ~300) spectra simultaneously, while leaving most of the focal plane free for imaging. A row of simple spectrographs could occupy ~25% of the focal plane, observing each target about 100s once per night. At its core, such a spectrograph would be straightforward to construct, since it is primarily a re-imaging system focused onto its own CCD and drift scanning only somewhat slower than the imaging detectors. We have several plausible concepts for a series of spectrograph slits that could also drift at the sidereal rate across the focal plane. Such a spectrograph could acquire a classification-quality spectrum of a $z \approx 0.5$ SN Ia over the course of a month. For galaxies, in 10 passes we could acquire spectra for measuring internal velocities (4Å resolution at 7000Å, $S/N \approx 15$) for a typical luminosity (L_*) galaxy at $z \approx 0.5$. By observing ~100 galaxies at once, one obtains roughly one million such redshifts per year. (There are more than enough such galaxies in 900 $\deg^2$.)

2.1 Dark Energy

The impact of the full ALPACA survey on the dark energy mystery would be truly overwhelming. To summarize the many cosmological tests this would empower:

The ALPACA Camera will detect photometrically 50,000 SNe Ia to $z \approx 1$ per year (plus many thousands of SNe II and Ib/c). For most of these classification spectra can be obtained and highly accurate redshifts from their host galaxies. Using the methods outlined above, we might achieve 0.003 magnitude statistical errors and plausibly reach comparable relative systematics. (The ALPACA filter system is designed to nearly eliminate K-correction errors, although their absolute calibration is a difficulty beyond the current scope).

With $> 10^6$ accurate spectroscopic redshifts for galaxies, we can measure the apparent position of the prime peak due to baryon oscillations at five to ten different redshifts for $0.3 \lesssim z \lesssim 1.5$. This will allow accurate measurements of the dark energy density at multiple epochs in the dark energy-dominated era, and be several times larger than current surveys (Eisenstein et al. 2004) in volume and ~10× greater in density.

The ALPACA filter bands will yield photometric redshifts accurate to $Dz \approx 0.1$ for an impressive sample of $\sim 10^9$ galaxies. With 0.23 arcsec pixels we have the potential for a massive weak-lensing survey, and photometric redshifts should produce a superlative "tomographic lensing" survey with impressive cosmological leverage. At 3 $\deg^2$ across, the weak lensing field subtends over 100 Mpc at $z = 1$, suffering negligible edge effects.

CMB anisotropies can be combined with optical data to place new constraints. The integrated Sachs-Wolfe (ISW) effect arises as CMB photons cool while traversing cluster potential wells in the expanding universe; the size of the effect depends on the acceleration of universal expansion. Our sample of ~50,000 galaxy clusters correlated with CMB temperature irregularities will yield the redshift evolution of the ISW effect, describing how the density of dark energy has changed (Corasaniti et al. 2003).

The growth of structure depends on whether normal matter dominates the expansion, so the redshift evolution of galaxy cluster numbers (adjusting for the strength of general clustering power) relates to the dark energy density. The constraint is much tighter when combined with CMB anisotropy constraints (Wang, Khoury, Haiman & May 2004). This approach has been approximated at lower precision using galaxies alone to constrain the power spectrum (Efstathiou et al. 2002).

These tests are each individually powerful enough to show how dark energy behaves dynamically, and can be intercompared as cross-checks. Further tests include the apparent shape of galaxy voids as influenced primarily by dark energy according to

Alcock-Paczynski distortion, and highly accurate time delay measurements in ~10 strongly lensed sources, allowing us to measure the Hubble constant at numerous redshifts. The combination of all these tests will have no rival among cosmological surveys now under consideration.

2.2. Science Capabilities Summary

Cosmology is not the only topic that will be greatly advanced by ALPACA. From very high redshift objects to near-Earth objects ALPACA will exhibit a great capacity to provide singularly powerful data sets. While its pointing is restricted, it surveys the center of our Galaxy and a large region in the South Galactic Pole region. There are many special objects in ALPACA's field, some of which are listed below. Some of these samples include:

- Well-sampled, 5-band SN light curves (to $r \sim 25$ each night, $r \sim 28$ each year) to discover and identify ~50000 SNe Ia and ~30000 SN Iab/II per year. SNe Ia mostly over $0.2 < z < 0.8$ range, which is ideal for detailing the evolution and dynamics of dark energy
- Weak Lensing: 700 square degrees with multiband data good for photometric z's
- Galaxy photometric redshift sample to $r \sim 28$; roughly 1 billion galaxies
- For galaxy clusters, should achieve same richness as SDSS cluster catalog (to $z = 0.3$) but to $z = 1$. Sample of ~30000 clusters
- Includes strong QSO lensing e.g., J12514-2914. Monitor 10-20 examples.
- Map of Sculptor supercluster ($z = 0.11$). Novae, bright variables.
- Should find several orphan GRB afterglows per year.
- Monitor 100,000s of AGNe to $r \sim 26$ for multiband variability.
- Large scale structure over 4 Gpc^3 (comoving) to $z = 1$ and 9 Gpc^3 to $z = 1.5$.
- Includes M83 (7 Mpc away, starburst); two Seyferts: NGC 2997 (17 Mpc), NGC 1097 (17 Mpc). Follow cepheids, miras, novae, eclipsing variables.
- Passes through Galactic Nucleus; will find >5000 Bulge microlensing events per year; superlative extrasolar planet search resource.
- Many 1000s of variable stars: Galactic structure.
- Huge variety of stellar surveys.
- Discover ~50 Kuiper Belt objects per night.
- Trace near-Earth asteroids of 1 km diameter to Jupiter's orbit, reconstruct orbits well within 1 AU and detect 50 m objects at 1 AU.

3. Telescope design

3.1. Optical design

ALPACA employs a unique optical design that provides high-quality images over a wide 3-degree field of view using only three reflecting surfaces. The modified Paul-Baker design uses an 8-m parabolic primary mirror, a mildly aspheric convex secondary mirror and a near-spherical concave tertiary mirror. This design gives excellent image quality (typical RMS spot diameters of 0.4 arcsec) over a 3-degree diameter flat field (Figure 2). Both the 1.7-m secondary and the 2.7-m tertiary mirrors are of conventional glass construction and can readily be manufactured by diamond turning.

3.2. Liquid primary mirror

ALPACA achieves a very high performance/cost ratio with the help of a new technology - rotating liquid mirrors. Newton first showed that the surface of a rotating liquid takes on the shape of a paraboloid. Modern liquid mirror telescopes have undergone considerable evolution since their introduction two decades ago (Borra 1982) and are now a mature technology. The 3-m NASA Orbital Debris Observatory (NODO) conducted a 7-year observing program to detect and characterize orbital debris; this program was so successful that the team received a NASA Group Achievement Award. The 6-meter Large Zenith Telescope (LZT, Hickson et al 2006, see also www.astro.ubc.ca/lmt/lzt), achieves an image quality that approaches that of the best conventional telescopes under similar seeing conditions. While the productivity of thje LZT is limited by the quality of the site, near sea level on the West Coast of British Columb1a, it has allowed us to develop and perfect the technology. Its 6-meter liquid primary mirror has been shown to have a surface accuracy of ~10 nm (about 1/60 of a wave, Hickson and Racine 2006). Most recently, the International Liquid Mirror Telescope project (ILMT), involving a collaboration of Univerersities in Belgium, Canada and India, is constructing a 4-m liquid-mirror telescope. The observatory will be located at Mt. Devasthal, a 2500m peak in the Indian Himalayas. The primary scientific program is a search for variable objects and gravitational lenses.

The ALPACA telescope design builds upon the successful LZT technology. The 8-m primary mirror will rotate on a massive air bearing designed specifically for this telescope—a scaled-up version of the LZT air bearing. The mirror will be driven by a brushless DC motor integrated into the bearing, with feedback provided by an integral high-resolution optical encoder. The mirror will be controlled by a dedicated computer that will update the motor torque one hundred times per second. The mirror itself will be made from nine machined aluminum mirror-segment castings that will be assembled on site. This design provides a more accurate surface (a typical surface error of ±100 um, compared to 300 um for the LZT). Also, because the entire structure is made from a single aluminum alloy, thermal expansion will be homogeneous and will not produce surface deformation. The mirror segments will fit within a standard shipping container and can be assembled with a minimum amount of labor.

The ALPACA mirror will have a removable mylar cover consisting of 50 pie-shaped segments extending between a central hub and the mirror rim. Each segment will be removable for periodic cleaning and/or replacement of the mylar film. The light loss introduced by the mylar cover is 24% (22% from dielectric reflection losses and 2% from geometrical shadowing by the frame).

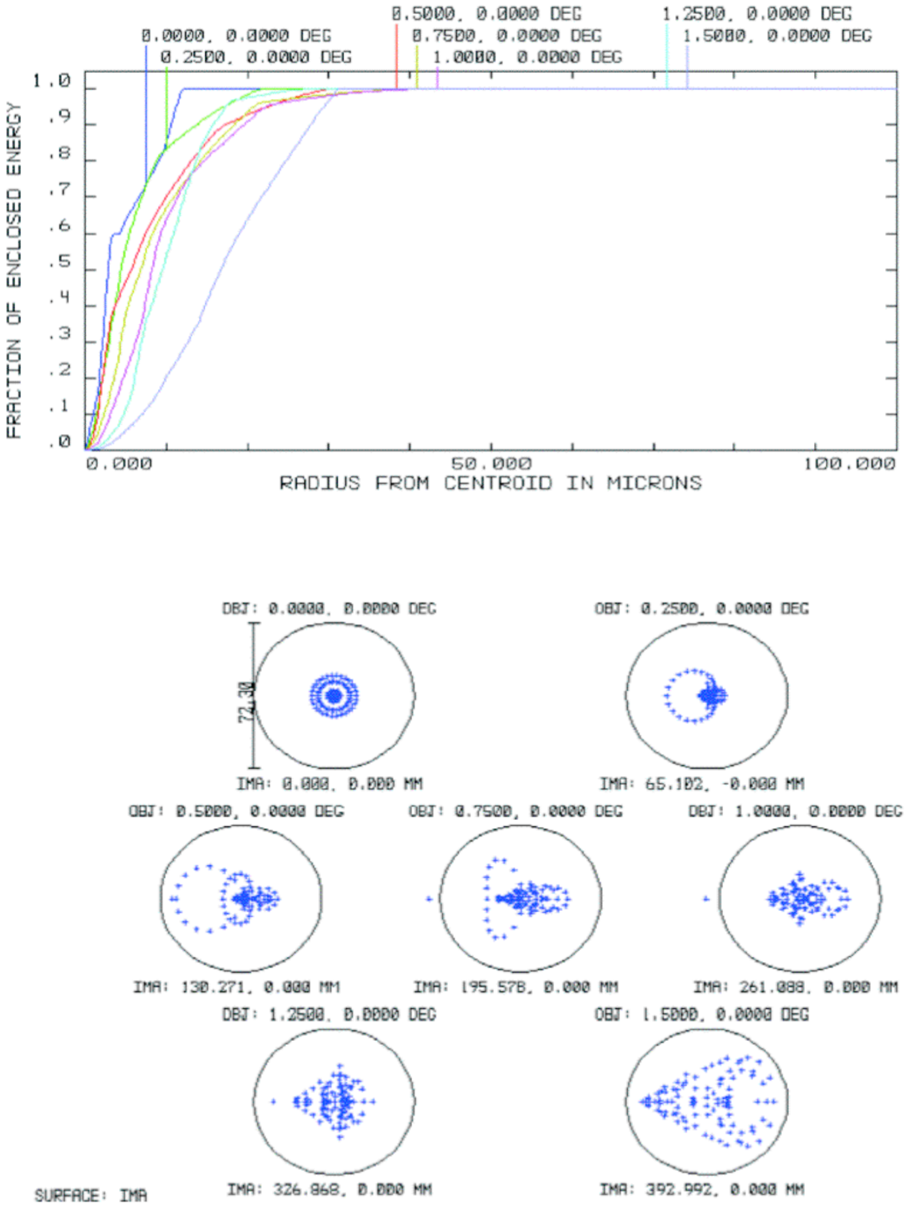
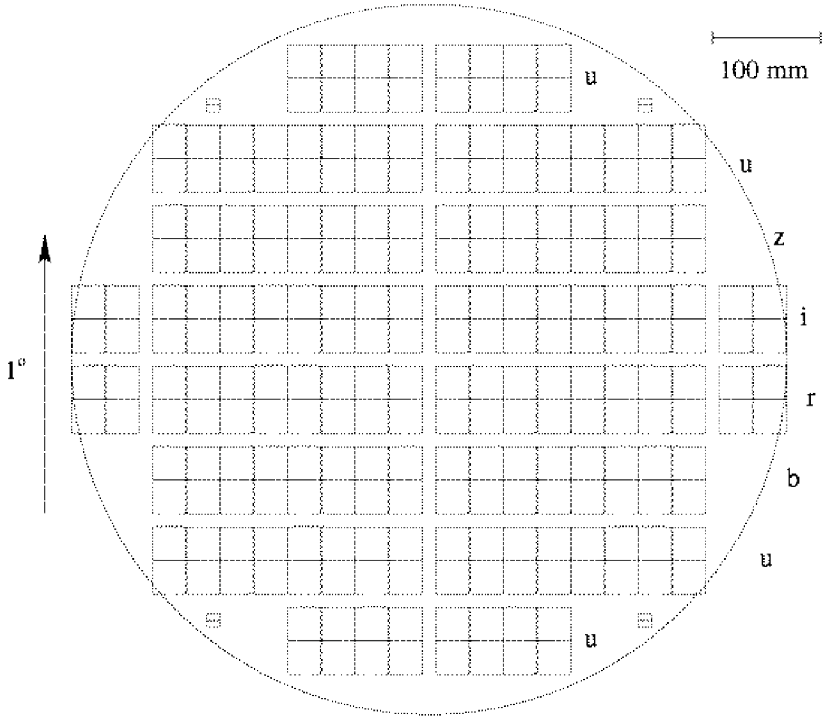


Figure 2: Top: Spot diagrams from the ALPACA wide-field optical configuration at field-angle intervals of 0.5 deg. RMS spot diameters range from 0.17 arcsec at the center to 0.5 arcsec at the edge of the 3 deg field. Bottom: Encircled energy versus radius for the same seven field angles. The image scale is 72.3 _m per arcsec. The 50% encircled energy diameters are less than 0.28 arcsec over the central 2.5 deg and increase to 0.47 arcsec at the edge of the 3 deg field.

3.3. ALPACA Camera

ALPACA will be equipped with a large imaging camera to cover the full 3-degree field of view. Similar in concept to the Sloan Digital Sky Survey Camera, It will employ rows of CCDs operating in time-delay-integrate (TDI) mode, each with individual fixed optical filters. One possible layout is shown in Figure 4. Sidereal motion carries objects across once CCD at a time, providing multi-colour photometry in a single pass. With this camera ALPACA can image 935 square degrees of sky, with simultaneous observations in five wavelength bands.

Fig. 3: 3-color image of galaxy from 100s drift-scan with 6 m LZT in 1.5” arcsec seeing.



240 Science CCDs, 4 Focus/Alignment CCDs
1.007 Gpix/32.2s = 2.25 TByte/10h

Figure 4: Possible layout of the ALPACA imaging camera. The arrow indicates the direction of sidereal drift. Letters indicate bandpasses of the filters that cover each horizontal row of detectors.

3.4. Observatory Design

The ALPACA telescope will be a zenith-pointing telescope that operates in "drift-scan" mode—continuously scanning a wide strip of sky passing overhead. This is a highly-efficient mode of observing in which 100% of the available observing time is spent taking data. Unlike conventional tracking telescopes, no time is wasted moving and acquiring targets or waiting for the camera to read out. This also allows great simplification in the design of the telescope and enclosure, and corresponding cost savings.

The ALPACA telescope will be housed in a steel-frame building equipped with a retracting roof. The entrance aperture of the enclosure will be at a height of approximately 15 m above ground level, in relatively undisturbed air above much of the atmospheric boundary-layer turbulence. The telescope and building are of low-heat-capacity structures to minimize thermal "dome" seeing. All heat sources within the enclosure will be insulated and ducted to prevent thermal convection.

The observatory infrastructure and support facilities will be in separate buildings detached from the telescope enclosure. A mechanical building will house air compressors, the air bearing pneumatic system, a backup generator and electrical and ventilation systems. A control building will house the main computers, telescope control room, electronic and vacuum system facility, and provide support for observers and visiting astronomers.

The mercury used for the primary mirror will be entirely contained and strictly controlled. As with the LZT, a pumping system (employing leak-proof peristaltic pumps) will transfer mercury between the primary mirror and a stainless-steel tank. Air in the tank and the space between the mercury and the mylar cover will be pumped through a charcoal filter to remove mercury vapor produced during pumping and startup operations. Mercury evaporation stops as soon as the oxide layer forms, approximately two hours after startup. The mirror normally runs continuously for weeks or even months at a time without any need to disturb the mercury. Standard safety procedures will be employed including continuous monitoring of air in the enclosure building with automatic mercury vapor detection equipment. It should be noted that four liquid-mirror telescopes have now been in operation for a combined total of more than twenty years with no incidents or accidents related to mercury. Monitoring has been conducted at NODO for the entire project.

3.5. Data Handling

The analysis of imaging data from the ALPACA program will be uniquely straightforward: each CCD will always observe the same portion of sky (0.13 deg wide by 310 deg long), in the same filter band, and always at the lowest possible atmospheric extinction. Each CCD, and the processor and software it feeds, is specialized and simple to implement by requiring that the same processor always deals with output from the same CCD. The biasing and flatfielding operations for driftscan data are one-dimensional operations (which can be handled by modifying slightly the open-source code PHOTO written for the SDSS, including other operations e.g., scattered light correction). Next once can compare the image from a CCD to a single reference image in order to find variable or moving sources, using image subtraction code very similar to that already developed (e.g., Alves et al. 2004). Software tested on NODO/LZT data had demonstrated that image subtraction is remarkably simple and fast, leaving no significant residuals for even bright, non-variable objects. All of these operations can be handled by one processor, then fed to a second processor for source-finding in the subtracted residual image, and then to source cataloging. The catalog, much reduced in size from the original image, can then be combined with catalogs from other CCDs and fed to central processor(s) to provide prompt alerts for SNe, GRBs, microlensing events, novae and asteroids, within 24 hours. A high-quality summed image for each field in each band serves as the subtraction reference image.

Additionally, each raw image, or an image reversibly derived from it (such as the subtracted image for deeper asteroid searches), is stored.

The data rate from the ALPACA Camera is expected to be 2.3 TB per night. This data rate is still transportable by hard disk express shipment. Alerts will be disseminated by email and webpage. To transmit the images for the full ALPACA dataset from Cerro Tololo to the outside world (at least to La Serena) will require upgrading the current downlink in a manner consistent with CTIO's plans and standard technology.

3.6. Site

We have already negotiated and arranged access to a superb site at the Cerro Tololo Inter-American Obser- vatory in northern Chile. The benefits of this site are (1) excellent weather and seeing conditions, (2) access to a well-developed infrastructure (including roads, utilities, dorms, etc.), and (3) a latitude which accesses interesting and important parts of the sky, including the Galactic center and the ecliptic plane. We are using equipment already developed and constructed by our team (including a lunar scintillometer and an array of microthermal sensors) to perform site testing to chose an actual location on the mountain top. Documentation regarding the site arrangements is included as supplementary documentation.

3.7. Schedule

We have completed more than three years of site testing, which should suffice, as well as a conceptual design review (CoDR) by an expert panel (Bob Williams, Jacques Beckers, Lynn Seppala) and passed with flying colors. ALPACA must pass through an additional preliminary design and critical design review, which would require one year. The CoDR determined that the first light on a scientifically interesting telescope with a prototype camera (1 deg FOV) would require approximately three years and $8M (including 25% contingency and 3 years operations), that the full imaging detector and survey would cost about $25M more and could begin two years later and produce a complete dataset in about three years, after which we would likely install the spectrograph at a cost of about $5M.

4. Impact for New York

The survey results for the desired New York State telescope must be considered in light of existing national and publicly-available facilities. Huge amounts of telescope time on small telescopes can be garnered on small telescopes via SMARTS, and significant time on 6-meter class, 8-meter and 10-meter telescopes can be won via Gemini and TSIPS resources. All one needs is a high-quality proposal to access these and other telescopes over a wide range of apertures and wavelengths.

What is unique about ALPACA is that it offers a singular data set, even deeper than that proposed for LSST (the same aperture but over a narrower field), and this is a uniquely-proposed but powerful data set. Nonetheless there is close precedent for a survey of this organizational design, the Sloan Digital Sky Survey, which is one of the most successful and productive collaborations, in absolute terms and by the dollar, of any in history. New York astronomers could have their own, unique "super-SDSS" realized by ALPACA, a unique resource of huge science potential. It is a rich prospective survey that opens many horizons in huge numbers of fields, yet dovetails with many upcoming surveys in other modes, in cosmology (Wiggles, BOSS, LSST, DES, JDEM or equivalent) and elsewhere (Pan-STARRS, ALMA, etc.). ALPACA will be New York's way of maintaining its position in an increasingly innovative and potent age of massive astronomical data sets. This will require honing local skills that will set many of New

York's junior astronomers in good stead for employment in this new environment. These huge data sets are where astronomy is headed, and New York will be firmly placed in the forefront.

While ALPACA is designed with largely off the shelf technology in mind, and while we have a relationship with Mike Lesser's lab at University of Arizona sufficient to deliver its focal plane, plus further relationship with optical engineers/designers (some mentioned above), the final optical design and focal plane engineering is work that could be accomplished by the considerable resources and expertise within New York State should they come onboard. Our team has considerable experience with the software pipeline issues for ALPACA, but considerable related expertise exists at IBM Watson and Brookhaven Lab (the latter being one of our collaborators on related LSST issues). The industrial partnership possibilities within New York State for ALPACA are strong. Our collaboration has already submitted a NYSTAR proposal with the Corning Canton facility (contact: Larry Sutton, 315-379-3200), have collaborated in related matters with ITT (formerly Kodak Rochester: contact Robert Egerman, 585-595-7065) and have discussed how we can collaborate with ALPACA. Furthermore the large-dimension interference filters required by ALPACA are probably best manufactured in New York (Semrock Rochester, contact John Kriegel, 585-594-7065). Corning in particular is a major resource. If we adopt a liquid mirror primary, the 1.5 and 2-meter secondary and tertiary mirrors are still multi-million dollar components, with a large share to be supplied by the efforts of Corning Canton. If, on the other hand, we were to decide that a monolithic solid primary was the best choice, Corning would be ideal to produce this. Much, if not most of the funds for ALPACA could be spent internal to New York. The costs in Chile (primarily labor) are impressively low.

Our model for a New York ALPACA collaboration would likely be based on the political structure of SDSS, in which teams of collaborators select particular projects, and in which they work under the agreement that all share-holders are allowed participation to these projects, and major initiatives are circulated through the shareholder community before the team for particular publications are selected. If this is a wholly New York-funded effort, we would propose that New York astronomers have exclusive access to these data for a considerable period (5 – 10 years), and that further dissemination be funded only after garnering federal funds. The strength of ALPACA is that it would strongly encourage New York's astronomers to work together, and provide a real, forefront motivation for meetings and collaborations based on our common interests. Indeed each commonly studied subfield of astronomy represented in New York would best be encouraged to have their own workshops so as to decide collectively how to exploit ALPACA data. No other project provides this potential for bringing New York astronomers together into a more unified research and educational whole. Our organizations' meetings will have real, forefront and urgent necessity in terms of organizing our research.

Currently the ALPACA consortium has drafted (but not adopted) a governing model in which member institutions can contribute one to three members to the ALPACA board depending on the level of financial or in-kind contribution. There is no reason why this concept could not be revised within the New York context, however. In terms of federal funding, we have found it fairly easy to adopt ALPACA efforts to the NSF MRI model (although our proposal has not yet succeeded). As we mentioned, we worked closely with Corning to develop a NYSTAR proposal and would encourage this approach again pending economic developments in New York and political decisions in the Governor's office. Columbia has also managed to generate some funding for ALPACA via private contributions, and has a number of successful fundraiser/contributors willing to form a development committee for an active ALPACA sponsorship push. We would bring this to bear with the encouragement of New York State.

If this project is funded in a NYAC context Columbia University could propose and would be willing to take on major project and database administrative responsibilities, but by no means wants to dominate them. We would be happy to see engagement by more institutions, in New York City, Rochester, Ithaca, Brookhaven/Stony Brook and throughout the State. We desire this to be a collective effort and inspiration. We want to provide a data set and a research and educational resource that will allow innovative projects across a wide range of New York's astronomical community.