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The Synoptic All-Sky Infrared (SASIR) Survey

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A Collaboration Between the University of California, the Mexican Astronomy Community, and the University of Arizona.

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1 Summary

We are proposing to conduct a simultaneous multicolor (Y, J, H, K) synoptic infrared (IR) imaging survey of the entire sky (above declination $\delta = -30^\circ$) with a new, dedicated 6.5-meter telescope at San Pedro Mártir (SPM) Observatory (Mexico). This initiative is being developed in partnership with astronomy institutions in Mexico, the University of California, and the University of Arizona. This 4–5 year, dedicated survey, planned to begin in 2017, will reach more than 100 times deeper than 2MASS [27], increasing the effective detection volume by more than one million. The Synoptic All-Sky Infrared (SASIR) Survey will reveal the missing sample of faint red dwarf stars in the local solar neighborhood, and the unprecedented sensitivity over such a wide field will result in the discovery of thousands of $z \sim 7$ quasars (and reaching to $z > 10$), allowing detailed study (in concert with JWST and Giant Segmented Mirror Telescopes) of the timing and the origin(s) of reionization in the early universe. As a time-domain survey, SASIR will reveal the dynamic infrared universe as never seen before, opening new phase space for discovery. Moreover, synoptic observations of over 10^6 supernovae and variable stars will provide better distance measures than optical studies alone.

SASIR also provides significant synergy with other major Astro2010 facilities, improving the overall scientific return of community investments. Compared to optical-only measurements, IR colors vastly improve photometric redshifts to $z \approx 4$, enhancing dark energy and dark matter surveys based on weak lensing and baryon oscillations. The wide field and ToO capabilities will enable a connection of the gravitational wave (e.g., Advanced LIGO and LISA) and neutrino universe – with events otherwise poorly localized on the sky – to transient electromagnetic phenomena. SASIR will enable the distribution of dust to be mapped more precisely and with higher dynamic range than currently possible, removing systematic bias in extragalactic distance and galaxy studies.

Technical Overview: The 6.5m primary mirror is already funded and casting will reach the peak temperature stage in late August 2009. The SASIR telescope and dome structure will be based on the Magellan or MMT design — with demonstrated capability to deliver excellent image quality in an $f/5$ beam over 1+ degree diameter. This will mitigate risk and speed development. The camera consists of reimaging optics, 3 dichroics and 4 separate focal planes each seeing ~ 1 degree diameter of the sky with an effective focal ratio of $f/2.5$. In total, there will be $124 \times 2k \times 2k$ arrays, constituting the largest IR imager ever constructed. Thermal emission control and weight/space constraints will present significant engineering challenges, but no new technical development is required. The *étendue-couleur* is more than 3 orders of magnitude larger than 2MASS and $>10\times$ that of VISTA. Still, data rates (\sim TB/night) are roughly $100\times$ smaller than those expected from LSST and can be accommodated with ongoing upgrades at SPM. Data management and archiving will be performed in the US. We expect to release survey data to the US and Mexican astronomy communities in incremental stages throughout the science operations, and to release transients at least as often as daily.

Current State of funding: SASIR is “pre-phase A,” having finished a *preliminary conceptual design* phase. The primary mirror is fully funded, but no other significant funding has been secured for this project to date. Support for the conceptual and preliminary design phases was solicited (in late 2008) from the NSF and the Consejo Nacional de Ciencia y Tecnología (CONACyT). Funding for a pathfinder multi-color optical-IR survey (“RATIR”) on the 1.5m telescope at SPM has been secured (through grants from NASA) and first light is scheduled in early 2010.

2 Key Science Goals

2.1 Unveiling the Lowest-Temperature Neighbors

Our understanding of stellar populations stems from our sampling of the immediate Solar Neighborhood. This sample is woefully incomplete for brown dwarfs (BDs), objects which are incapable of sustaining core Hydrogen fusion. With masses extending from $\sim 0.075M_{\odot}$ to below $\sim 0.013M_{\odot}$ (the hydrogen and deuterium-burning minimum masses) BDs probe the low-mass limits of star formation processes and serve as a bridge between stellar astrophysics and planetary science. Lacking nuclear energy generation, they evolve steadily to low luminosities and low effective temperatures and are thus useful chronometers for a variety of Galactic studies (see following Astro2010 Whitepaper [WP]: Burgasser). They ultimately achieve photospheric conditions similar to those of gas giant planets ($T_{\text{eff}} \approx 100 - 1000\text{K}$). Overall, studies of BD populations and their atmospheres support a wide range of scientific endeavors: providing discriminating constraints on star- and planet-formation theories; driving advances in the properties of cool atmospheres; and guiding direct detection strategies for exoplanets. Testing models of BD atmospheres, and identifying true analogues to directly detected exoplanets (e.g., Formalhaut b, $T_{\text{eff}} \approx 500\text{K}$; [15]) will require detailed studies of BDs cooler than those currently known ($T_{\text{eff}} \approx 600\text{K}$).

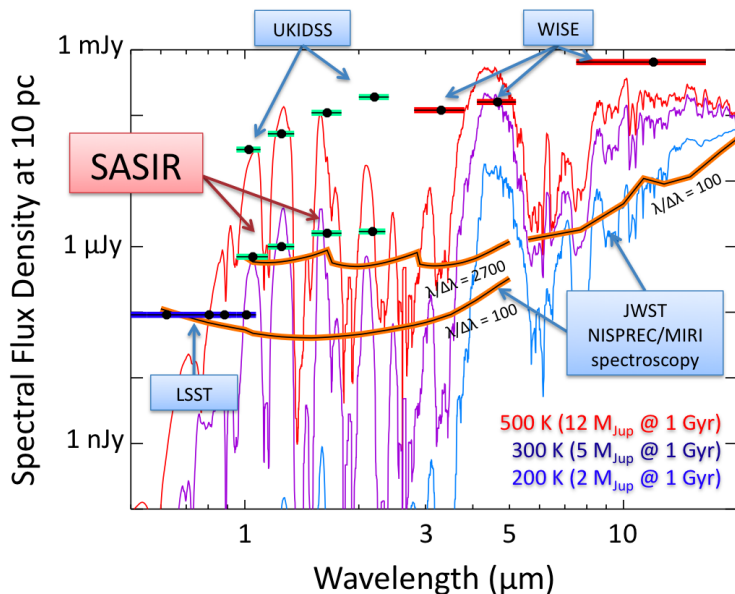


Figure 1 *Model spectra [5] for 500 K, 300 K and 200 K brown dwarfs (top to bottom), scaled to a distance of 10 pc. These models correspond to masses of 12, 5 and 2 Jupiter masses at an age of 1 Gyr, respectively. Sensitivity limits for current and proposed imaging surveys (including SASIR) and spectroscopic facilities (5 σ in 1 hour) are indicated.*

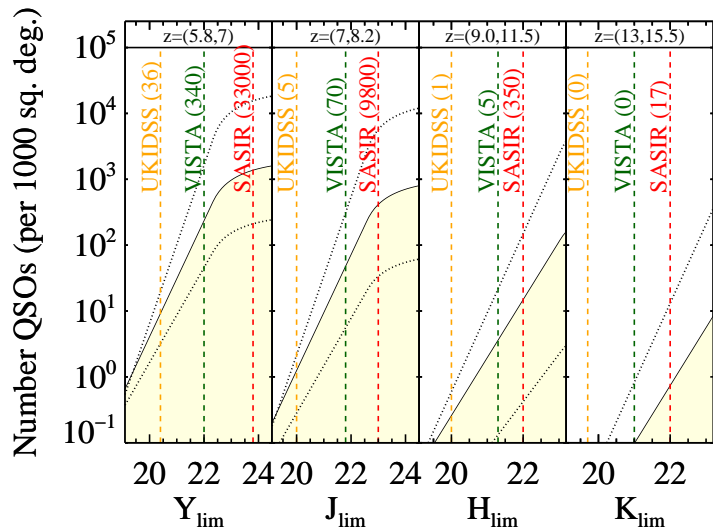
UKIDSS [17] and the pending WISE [8] experiments should detect the first $T_{\text{eff}} \approx 500\text{K}$ brown dwarfs within 10 pc (Fig. 1), but deeper optical/NIR surveys are required to extend samples to lower T_{eff} and beyond the local neighborhood. SASIR will provide a 100-fold increase in sensitivity over current NIR surveys, facilitating the detection of 1000K brown dwarfs out to 1 kpc (sampling the Galactic scale height of BDs), 500K brown dwarfs out to 100 pc (a 1000-fold increase in sampled volume over UKIDSS) and 300K “water-cloud” brown dwarfs out to 10 pc. This will help **complete the census of stars and BDs down to the lowest masses in the immediate Solar Neighborhood**, while sampling the density structure of brown dwarfs far from the Galactic plane. The multi-band and multi-epoch detections with SASIR, optimized in cadence for parallax

discovery and proper motion studies, in conjunction with single-band detections and upper limits from WISE in the mid-IR and LSST in the optical, will enable robust color- and motion-selection of sources for efficient spectroscopic follow-up with GSMTs and JWST. Expansion of the local census will also enable direct imaging searches for Earth-mass exoplanets and other companions with next-generation high-angular resolution facilities.

2.2 Probing the Epoch of Reionization with Quasars

With no in situ observations, the objects responsible for the reionization of Hydrogen beyond $z \approx 7$ span a wide range of theoretical possibilities [19, 23] (WP: Prochaska, McQuinn, Bouwens, Stiavelli). The consensus is that bright quasars (QSOs) have insufficient number density at $z > 5$ to drive reionization [e.g., 11], but AGN remain the only extragalactic source known to have high escape fractions of ionizing radiation. Surveys for $z > 5$ QSOs have observed the brightest sources, leaving the faint end of the luminosity function mostly unconstrained. If the faint end steepens (as for high z galaxies in the UV) or if entirely different classes of AGN [e.g. mini-quasars; 18] exist at early times, these would contribute to the extragalactic ultraviolet background at $z > 5$. Independent of reionization studies, surveys for $z > 6$ QSOs are also valuable as tracers of the growth of supermassive black holes (BHs) that populate modern galaxies or as signposts for follow-up studies of early galaxy formation [1, 6]. In the next decade, it will be possible to **determine the nature and role of QSOs during reionization** with SASIR as a major contributor.

Figure 2 Predicted surface density of quasars (solid black line) per 1000 sq. deg as a function of limiting magnitude assuming a double-power law luminosity function with $\beta_l = -1.64$, $\beta_h = -3.2$, with $M_{1450}^* = -24.5$ and $6 \times 10^{-10} \text{ Mpc}^{-3}$ quasars brighter than $M = -26.7$ [9]. The curves assume a number density evolution $\propto \exp(-0.43z)$. The dotted lines indicate more optimistic and pessimistic assumptions on the number density and redshift evolution. The vertical lines indicate the magnitude limits of UKIDSS, VISTA, and SASIR with the number of detections given the proposed survey area in parenthesis. Only SASIR survey will have the depth and sky coverage to provide a meaningful sample of $z > 7$ quasars and have a realistic chance of detecting sources at $z > 10$.



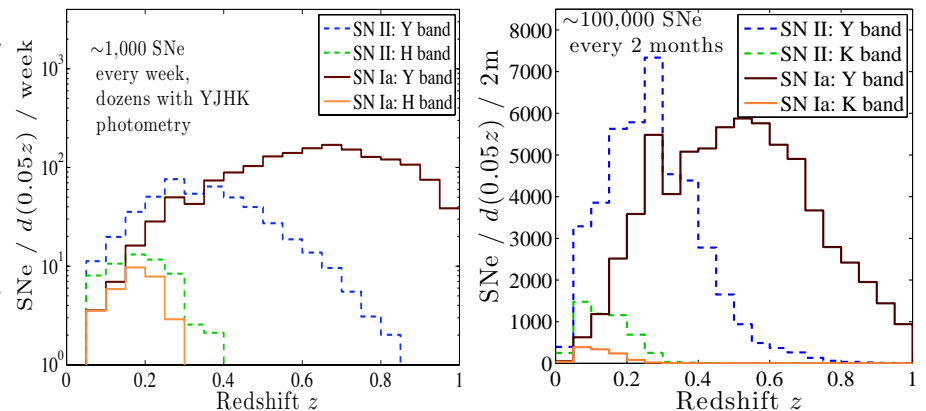
QSO searches in the reionization epoch are challenged by three effects: (i) cosmological dimming; (ii) low number density; and (iii) their extremely red color. Thus, high z QSO surveys require deep near-IR and optical imaging over a large area of sky. While SDSS and 2DF (and the upcoming Pan-STARRS project) provide large areas of optical imaging, no project has achieved comparable depth and area in the near-IR. The nearly completed UKIDSS and the upcoming VISTA surveys (a joint UK/ESO venture) should increase the current samples, but these programs also lack sufficient depth and/or area to meaningfully constrain the QSO population, especially at $z > 7$ (Fig. 2). A systematic study of AGN during the reionization era requires the survey characteristics of SASIR.

At $z \sim 6$, such surveys would establish the QSO luminosity function (surpassing even LSST for reddened AGN) and are necessary for sampling even the brightest sources at higher z . These measurements would be compared against estimates of the black-hole merger rate at $z \approx z_{\text{reion}}$ from gravitational-wave experiments (e.g. LISA).

2.3 The Cosmic Distance Scale, Dark Matter and Dark Energy

An IR View of Periodic Variables in the Local Universe: Pulsating variable stars (WP: Walkowicz) are preeminent distance indicators in the local universe. When RR Lyrae and Cepheids are used, however, unmodeled dust and metallicity effects manifest directly as uncertainties in cosmological parameters [3, 29]. SASIR would allow for precise calibration of the period–luminosity (P-L) relation of these two classes in the IR, largely skirting the problems with dust (and potentially metallicity [28]) which complicate similar efforts at optical wavebands. Multiple observations at random phases would build an unprecedented calibration of the P-L relations and enable GSMTs to measure precise distances well beyond the Local Group and fix the rungs of the cosmic distance ladder out to ~ 25 Mpc. Mira variables, promising new distance indicators, would also be observable with SASIR to ~ 4 Mpc with what appears to be a metallicity independent P-L relation [12].

Figure 3 *Expected SN counts for two types of surveys with SASIR: a rolling search with weekly cadence (left), and “all-sky” monitoring every two months (right). The number of SNe in the different surveys is inversely proportional to the light-curve information we will have for each SN. The samples are complementary and both have cosmological use.*



Infrared Supernovae: Type Ia supernovae (SNe Ia) (WP: Howell) are better standard candles in the IR than at optical wavebands [32] and minimize systematic effects that plague Ia optical cosmography. Type II-P SNe are an emerging distance indicator (e.g., [24]) recently shown to be almost comparable in precision to SNe Ia ([22]; WP: Poznanski), and could be even better standard events in the IR. In addition to cosmography, searching for SNe in the IR will improve our understanding of their rates (largely circumventing dust effects) and hence constrain their diverse progenitors. Using optically determined rates alone, SASIR will detect more than 10^6 SNe during the four-year survey (Fig. 3).

Photometric Redshifts for Weak Lensing and Baryonic Oscillations: Wide-field IR photometry provides a compelling improvement in the photo- z measurements of galaxies, especially beyond $z \sim 1.5$ (Fig. 4, left). The enhanced accuracy for galaxies across the Northern sky will greatly improve the returns on weak lensing and baryonic oscillation experiments with wide-field optical facilities (WP: Riess, Eisenstein, Heap, Zhan)

Galaxy Evolution and High-redshift Clusters: A frontier endeavor for the next decade will be

to determine the progress of nascent galaxies as a function of local environment as they proceed from the “blue swarm” of small star-forming objects at $2 < z < 3$ to the well-defined red sequence of massive galaxies seen in both galaxy clusters and the field at $z < 1$ (WP: Holden, Labbe, Stanford). The appearance of the red sequence will probably spread from the high- to low-density environments, such as groups, before becoming established in the field. Such a study requires identifying the full range of environments at $z > 2$, through wide-area imaging, since halos of mass $M > 10^{14} M_{\odot}$ are exceedingly rare at $z > 2$ (Fig. 4, right).

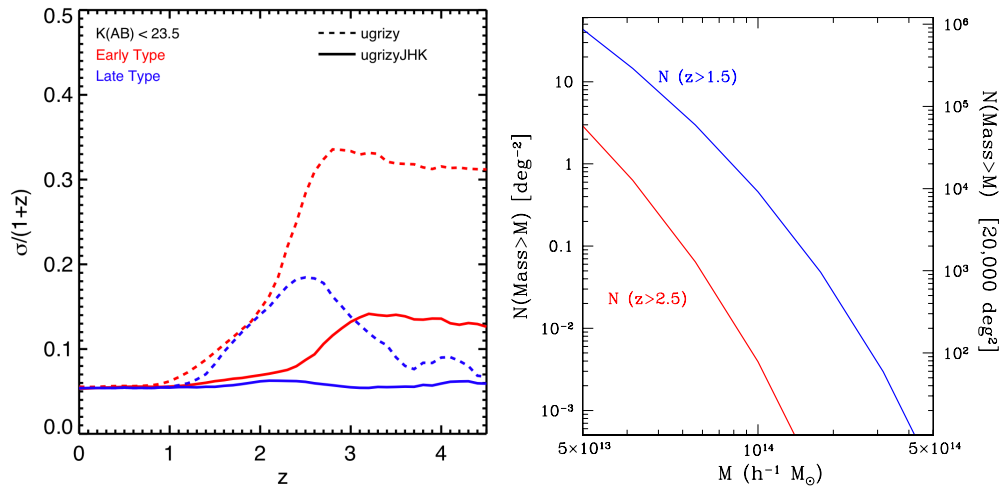
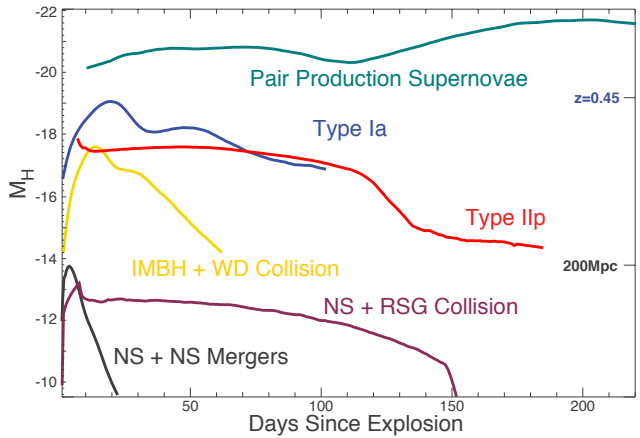


Figure 4 (Left) Simulated photometric redshift accuracy for early (red) and late-type (blue) galaxies. Dashed lines show the expected performance of LSST/Pan-STARRS4 alone. Solid lines include NIR data from SASIR, which vastly improve accuracies at $z > 1$. Simulations assume a 4% floor to these accuracies [4]. (Right) Expected cluster demographics by mass in two redshift regimes. Finding the rarest massive clusters requires a wide-field near-IR imaging survey so that galaxy populations at $z > 2$ are selected at rest frame wavelengths.

2.4 A New Phase Space for Transient Discovery

Deep multicolor synoptic monitoring on hundreds to thousands of square degrees on minutes to months timescales would break new ground in the infrared, opening up the potential for totally new classes of objects found by IR variability. There are indications that exploration in this space phase will be fruitful (e.g., WP: Kulkarni Wozniak, York), particularly relevant to “multi-messenger” astrophysics. Indeed the explosive events which dominate the high-energy sky — involving compact objects such as neutron stars (NSs) and BHs (BHs) (of both the stellar and supermassive varieties) — should produce long-wavelength signatures (Fig. 5). Motivating the need for wide-field monitoring, TeV gamma-ray Čerenkov telescopes and neutrino detectors will localize events only to degree-scale accuracy. Likewise, Advanced LIGO and LISA are expected to localize degenerate object merger events through gravitational waves (GW) with, typically, one-degree scale uncertainties. Much of the science extracted from these new windows on the universe will require the identification of electromagnetic counterparts, which would yield the redshift of the host galaxy and enable their use as standard sirens for cosmography [16, 26] (WP: Bloom). Little is known of these signatures but indications are that the IR is a valuable window [Fig. 5; 14, 25] (WP: Hawley, Phinney, Bloom). As such, SASIR, with its rapid access to deep wide-field imaging is a promising tool.

Figure 5 *Characterizing the transient universe at IR wavelengths. Aside from the “known” Type Ia (blue) and core-collapse (red) SNe, new types of extragalactic transients are expected to arise from cataclysmic events. Shown are our estimated restframe infrared light curves resulting from the collision between a NS and red supergiant (RSG; purple), the disruption and ignition of a white dwarf by an intermediate mass BH (yellow), and the merging of a NS binary (powered by r-process nucleosynthesis; black). SASIR will readily see NS-NS mergers to the Advanced LIGO volume (see § 2.4). These preliminary model calculations suggest that an assortment of peculiar transients should be uncovered by SASIR, providing a complementary view (less obscured by dust) of the transient universe than that offered by optical syn-*



2.5 Broad Scientific Reach and Synergies with Other Major Facilities

The above discussion highlights the expected impact of SASIR in just some of the fields of interest in the next decade. Many of these areas were covered in the whitepapers generated by our collaboration. The following lists additional examples with hypertext links to science WPs submitted by us and other groups to Astro2010:

- Discover new satellites of the Galaxy minimizing dust biases (WP: Bullock, Johnston),
- Produce large new samples of strong lenses (WP: Coe, Koopmans, Marshall),
- Survey the oldest (i.e. coldest) white dwarfs in the Milky Way (WP: Kalirai),
- Produce a Galactic dust-extinction map of unparalleled spatial resolution (WP: Gordon),
- Probe the bright end of the galactic luminosity function at $z > 5$ (WP: Bouwens),
- Stellar population analysis of nearby galaxies (WP: Kalirai, Kirby, Lu, Meixner, Worthey, Wyse),
- Discover star cluster systems (WP: Rhode),
- Study stellar morphology (bulge/disk) in nearby galaxies (WP: Clarkson),
- Map the distribution of low-mass stars well beyond the solar neighborhood (WP: Cruz),
- The search for light bosons (WP: Chelouche),
- Finding Type II_n SNe at $z > 5$ (WP: Cooke),
- Probing quasar variability (WP: Elvis, Murray),
- Long-wavelength signatures of tidal disruption events (WP: Gezari),
- Exploring the nature of X-ray and explosive transients (WP: Soderberg, Wozniak),
- Studies of variable stars from near to far (WP: Walkowicz)

It is worth emphasizing that many of the science WPs submitted to Astro2010 have called for wide-field, near-IR surveys of the sky. While some science goals demand the high spatial-resolution afforded by space missions, most could be done for far less expense by a ground-based observatory like SASIR.

3 Technical Overview

The enormous scientific promise of SASIR is based on a dedicated wide-field (1 degree diameter) large aperture telescope (6.5 m in diameter), located in a dark site with a large fraction of clear nights ($\sim 75\%$), enabling deep and synoptic imaging of the whole Northern sky simultaneously in NIR bands (Y , J , H and K) with four independent focal planes.

This uniquely powerful survey and facility does not require new technology exploration nor a totally new kind of telescope. Indeed, as described in §3.1, the SASIR telescope design will use already proven and operational concepts (such as from the Magellan and MMT telescopes) as the point of departure. Nevertheless, given the confluence of a moderately wide field with multiple and large focal planes, its actual design and technical feasibility with present day technology and IR materials needs to be carefully studied in the *preliminary design phase* (see §6, the schedule of proposed activities).

3.1 The 6.5-meter SASIR Telescope

The telescope structure and primary mirror are to be based on the highly successful and efficient Magellan Telescopes in operation at Las Campanas Observatory in Chile and the MMT telescope at Mt. Hopkins. The Magellan and MMT optics and structures are each well suited to wide-field imaging. In particular, a successful one-degree $f/5$ corrector has been in operation at the MMT [10] while a second system is being commissioned at Las Campanas. Furthermore, we have demonstrated [13] that this design is quite capable of delivering fields of view beyond 1.5° in diameter. The three main challenges facing the design of the SASIR telescope are therefore of a different nature:

- Simultaneous feeding of up to four focal planes, with collimator/camera NIR optics of reasonable size;
- Controlling spurious thermal emission in the H and K bands (under a proper baffling system, coupled with space for a cold pupil);
- Maintaining the instrument within the weight and envelope limits of the Magellan or MMT structure.

The first challenge above not only drives the survey speed but makes SASIR different and quite powerful with respect to its closest relatives, the 4m-class VISTA and UKIDSS systems and the 8m LSST. During 2009, the SASIR collaboration will be developing its telescope concept by fully investigating and resolving among potential telescope solutions that optimize the science returns and minimize the risks of the camera design: a conventional telescope plus image reducer(s), as here presented, a 3-mirror telescope with an intermediate collimated beam, or a conventional telescope with dichroic(s) in non-parallel beams.

A range of variants on the base Magellan design are currently under consideration to find a solution that will permit up to four individual-band cameras, each with $\sim 1^\circ$ field of view (FoV), with NIR refractive optics under about 500 mm in diameter. The current reference concept consists of a $f/5.5$ Ritchey-Chretien design with a 3-lens field corrector (all spherical, Silica-like glass). In order to allow for a cold pupil as well as the placement of dichroics, the telescope is coupled

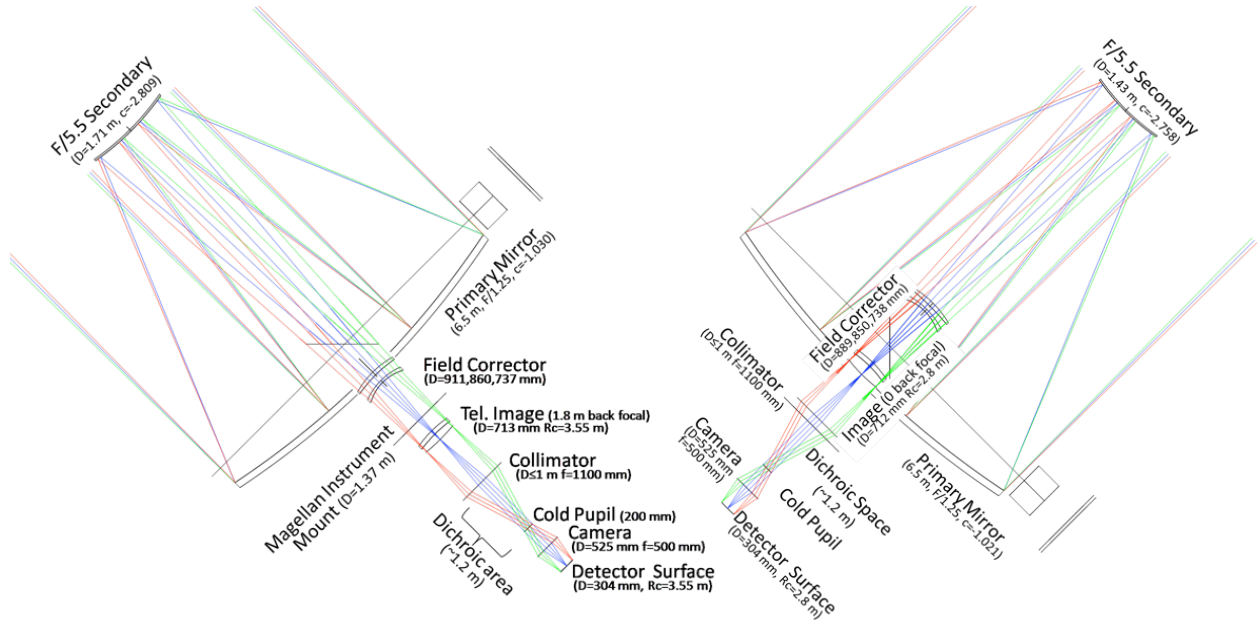


Figure 6 SASIR telescope designs (Magellan nominal back focus at right, null back focal at left). A single arm is shown with indicative camera and collimator parameters (folding dichroics not drawn). The telescope and corrector deliver an effective $f/5.5$ focal, the whole system is $\sim f/2.5$. Relevant characteristics of the main components are shown. These two baselines will be studied (optics, mechanics, costing) in detail.

to a focal reducer, with a collimated beam of 200 mm and a camera with focal length of 500 mm. Figure 6 shows two examples of the telescope concept, the first one maintaining the back focal distance of Magellan, while the second telescope focuses at the primary vertex, exploring the range in which the diameter of the secondary and the height of the pupil can be controlled. The present studies include cases for telescope f -ratios from $f/3.5$ up to $f/11$, at both Cassegrain and Nasmyth stations, and a range of pupil diameters. The designs shown deliver an image quality close to the diffraction limit across the whole FoV, between $0.03''$ and $0.1''$ FWHM. These idealized (pre-construction) telescope performances indicate that most of the optical error budget can be left for the more difficult collimator and camera designs, as well as for the construction and operation of the entire system. These telescope concepts let us explore the main parameter space and general dimensions for the SASIR collimator and camera systems. The full range of parameter exploration expected during the conceptual and preliminary design phases is detailed in Table 2.

3.2 The SASIR Camera

Foreoptics: SASIR plans a split-beam design for the camera optics, like 2MASS, to simultaneously image in 4 filters. The full optical design of SASIR will be driven by the following guidelines and constraints: the aperture and curvature of the primary mirror ($f/1.25$), a FOV of 1.06^{circ} , a plate scale of $\approx 0.228''$ per $18 \mu\text{m}$ pixel ($f/2.5$ net system), an after-construction-under-operation image quality that does not deteriorate by more than a few percent the median NIR seeing, a high-throughput design (e.g. efficiency $> 30\%$) at least within the $\lambda = 0.8\text{--}2.4 \mu\text{m}$ range, and a system

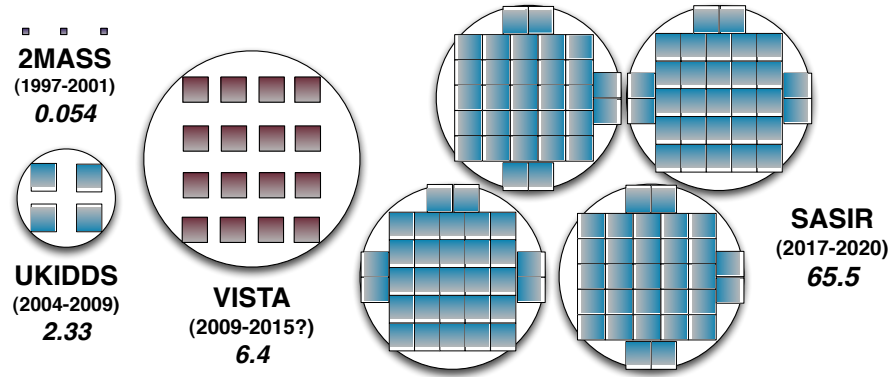


Figure 7 To scale physical comparison of the focal planes of 2MASS, UKIDDS, VISTA and SASIR. The *étendue-couleur* ($m^2 \text{ deg}^2 \times \text{number of simultaneous bands}$), the instantaneous light grasp, is shown for each facility.

with low thermal emission from its optical components that also permits the proper buffering of scattered thermal emission. The conceptual designs of the collimator and camera, based essentially on a scaled version of already known systems (e.g. FourStar NIR Camera for the Magellan Telescope; [21]), will be developed in parallel and share optimization constraints with the telescope concept.

Detectors: Given the expense for science-grade IR detectors (§7), our design is driven by a desire to cover a large field of view with the fewest pixels while still adequately sampling the good seeing at SPM. The nominal detectors are 2048×2048 arrays with 18 or $20 \mu\text{m}$ pixels, now commercially available.¹ This translates to $0.228 - 0.25 \text{ ''/pixel}$. We are baselining 124 science-grade arrays (Figure 7). SASIR will not be sensitive to the read-noise of the detectors, as even short exposures are expected to be background limited. We will thus allow for as flexible and dynamic imaging as the science requires.

3.3 Survey Strategy and Cadence Optimization

The Survey optimization will be revised in detail during the *preliminary design*, accounting for the articulated priorities of the diverse science cases. The baseline plan calls for 20 second double-correlated exposures – this optimizes on-sky exposures without saturating fainter 2MASS stars (which will be crucial for establishing the photometric baseline). For a total on-source dwell of 80 seconds (2 visits per night consisting of 2 integrations each) and nominal slew time to next field of 6 seconds, we expect to cover about 140 sq. deg per 8-hour night, implying that the entire visible sky from a single site could be imaged every 2–3 months. Table 1 shows the expected point source and extended source sensitivities (see also Figure 8). The simplest survey strategy would be to cover the sky repeatedly with roughly equal time between visits. Over a 4 year survey, each position could be observed ~ 6 times. To determine the parallax and proper motion of objects in the solar neighborhood (§2.1), we require at least three visits per field. In practice, there will be

¹The SASIR collaboration has built a strong working relationship with the two main vendors of IR arrays (Teledyne and Raytheon) and we have gained confidence that the necessary volume of arrays can be delivered on a timescale shorter than the telescope construction time.

Table 1. Nominal Sensitivities from SASIR Concept Design

Filter	Point Source Sensitivity				Extended Source Sensitivity	
	Single Epoch ($5\text{-}\sigma$)		Survey ($5\text{-}\sigma$)		Survey ($5\text{-}\sigma$ per pixel)	
	[AB mag]	$[\mu\text{Jy}]$	[AB mag]	$[\mu\text{Jy}]$	[AB arcsec $^{-2}$]	$[\mu\text{Jy arcsec}^{-2}]$
Y	23.49	1.45	24.47	0.59	23.32	1.71
J	22.95	2.40	23.93	0.97	22.78	2.82
H	22.60	3.30	23.57	1.35	22.42	3.89
K_s	22.47	3.74	23.44	1.52	22.29	4.40

Note. — Based on a preliminary simulation of a four band survey (Y and 2MASS filters J , H , K_s) with 75% clear weather fraction and average seeing of 0.6 arcsec and 18 μm pixels. Each epoch assumes 80 sec total integration with 6 epochs per field over the entire survey (24,000 sq. deg.). As a consistency check to the simulation, note that the 5σ limiting magnitude of 2MASS (1.3m diameter, 7.8 s integration, seeing $\sim 2.5''$) was 17.55 AB (346 μJy). For sky-limiting imaging, the limiting magnitude increases as $2.5 \log_{10}(\text{diameter time}^{0.5}/\text{seeing})$, with diameter, time, and seeing expressed as ratios. For the nominal six visit all-sky survey, this implies a nominal depth of 5.4 mag fainter than 2MASS.

several different cadence strategies, with both competing and complementary goals. For instance, a fast transients search would yield very deep imaging in several hundreds of degrees squared. The SN search (§2.3) would benefit from repeated scans of the same part of the sky every few nights, while a search for high proper motion objects would only require repeat observations on a months to years timescale.

3.4 Data Taking and Data Management Strategies

SASIR Data Management will benefit from direct experience with the Peters Automated Infrared Imaging Telescope (PAIRITEL) Project [2], the largest time-domain robotic telescope operating at infrared wavelengths. In particular its low-level telescope and camera interfaces, pipeline and archive system, and autonomous scheduling system are a reference for determining a baseline datataking strategy commensurate with instrument limitation and SASIR science goals. We envision that the Data Management architecture, developed fully in the conceptual design phase (§6), will most resemble that of Pan-STARRS, UKIDSS and VISTA.

3.5 Project Site and Required Infrastructure

The site, located in the northern part of Mexico in the Sierra San Pedro Mártir in the state of Baja California at an altitude of 2890 m, has been developed over the last forty years and has three telescopes with main optics diameters of 2.1-, 1.5-, and 0.84-m, with a number of photometric, spectroscopic and imaging capabilities in the optical, near-, and mid-infrared regimes. SPM excels in the transparency and darkness of the night sky as well as in the seeing quality and stability [7, 30, 31]. Comparison with other sites suggests that SPM has the largest percentage of clear nights of any site in the Northern Hemisphere. The median seeing reported by Michel et al. 20 is 0.6'' in the V band. It is yet to host a competitive next-generation telescope facility that fully exploits

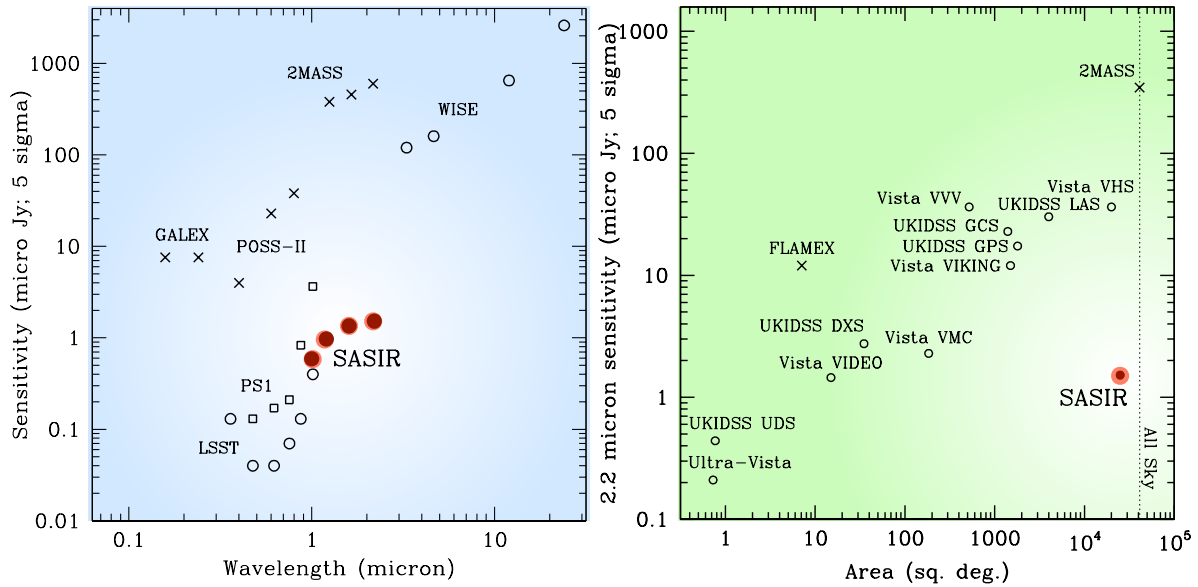


Figure 8 Comparison of the nominal SASIR survey with other significant surveys already completed (\times symbol) or planned (\circ or square symbol). Left: The point source sensitivity versus wavelength for wide-area surveys where we have assumed 6 total visits (480 s) for SASIR. Right: The point source K-band sensitivity versus sky coverage. The other survey data for these figures were compiled by D. Stern (JPL).

its unique virtues. The site had been considered by the LSST consortium prior to the decision to locate it in Cerro Pachón (Chile), as well as by next-generation extremely large telescope projects, such as the Thirty Meter Telescope (TMT).

The road that climbs the Sierra is paved up to the entrance to the National Park, while the last 16 km (within the park) is being completed now. Ample lodge and workshops at the Observatory are located 2 km from the telescopes and the selected SASIR site. The Observatorio Astronómico Nacional (OAN) has five electric generators with capacities of 280, 230, 200, 150, and 90 kw, respectively, but plans to soon connect SPM to the public electric network. This new line will also carry a fiber-optic network for a very high speed network, upgrading the current microwave link. IA-UNAM has a research branch in nearby Ensenada with a staff of 25 astronomers and a similar number of technical staff and students. IA-UNAM-Ensenada also serves as the logistic and administrative station for the observatory at SPM. Given the state of the present and planned infrastructure on the site, SASIR does not require, other than the facility itself, further major construction at SPM.

3.6 Design Considerations for the 2nd-Phase Operations

The SASIR Telescope is expected to be operational for 30+ years, well after the SASIR Survey is completed. The consortium envisions the telescope to continue mostly as a dedicated surveying facility. The current plan is to perform a wide-field optical/NIR spectroscopic survey, making use of the large detector investment. The SASIR telescope will be designed so as not to preclude or undermine the feasibility of such a multiobject spectroscopic survey.

4 Technology Drivers

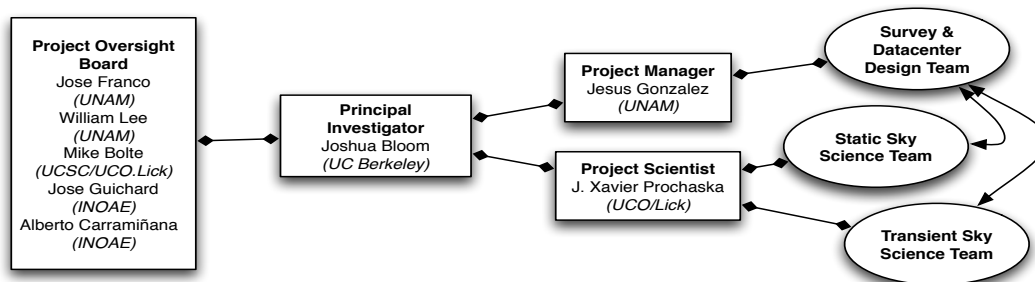
While the construction of a 6.5m telescope and a wide-field 4-channel IR camera will be an ambitious undertaking, we have not identified any truly “new technologies” that would need to be proven in advance of construction. To be sure, there are significant technical challenges and risks will need to be retired appropriately (see §6.1). For example, it is unclear that current optics vendors can produce sufficiently large, IR transmissive optics for the proposed wide-field cameras. Such concerns will be addressed in the design phases and may be mitigated by other (larger-scale) projects that have similar needs, e.g. GSMT.

5 Activity Organization, Partnerships, and Current Status

Project History & Current Status: The SASIR initiative started in late 2007 and the design is still at a *preliminary conceptual level*. No significant funding for the project itself has been granted, though several major proposals for support of the design phase were solicited in both the US and Mexico starting in Fall 2008. The preliminary conceptual design was created in tandem with the development of the SASIR science case over 2008, culminating in the production of a preliminary whitepaper by the collaboration for dissemination to members of the institutional partners. Two principals meetings were conducted in the first half of 2008 (in Santa Cruz and in Mexico City). A two-week collaboration workshop, with >40 people in attendance, was held in Puebla, Mexico in August 2008. The most significant engagement (face-to-face meetings, regular telecons) with third party vendors to-date has been with detector manufacturers (Raytheon and Teledyne). The casting of the primary mirror is currently underway.

Institutional Partners: SASIR is an international partnership between the University of California, Instituto de Astronomía at Universidad Nacional Autónoma de México (IA-UNAM), the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), and the University of Arizona. The SPM site (OAN) is operated by UNAM. The University of Arizona (developer of the Magellan/MMT mirrors) was commissioned by INAOE for the casting and figuring of the primary mirror. INAOE and the University of Arizona co-share ownership of the primary mirror. Extending partnerships, particularly to US and Mexico national funding agencies (CONACyT, NSF, etc.), is a priority for the collaboration. Other university or national laboratory partners may be solicited pending the outcome of private fundraising activities (see §7).

Current Project Management: All work on SASIR has been through in-kind contributions by the various principals involved in the project. The diagram below shows the current structure of the collaboration as we finish the *preliminary conceptual design* phase. A reorganization (and ex-



pansion) of the management structure is expected with the first round of funding for the *conceptual design*.

A Pathfinder Instrumentation Project: Our collaboration has begun construction of a new camera, the Reionization & Transients Infrared (RATIR) Camera, to be housed on the 1.5m telescope at SPM. The 2-year experiment has its own transients science drivers, but will serve as an important pathfinder for SASIR development: RATIR will be used for collaboration building, to engage 3rd party vendors and to help the collaboration gain first hand experience with the detector operations in advance of SASIR. RATIR will obtain nightly transmission and sky brightness statistics in Y , J , H for the duration of that experiment; this will directly feed into the SASIR survey simulations. As of now, we have only limited information about the SPM IR sky background as a function of lunar phase and almost no information about the Y -band site metrics.

6 Activity Schedule

The SASIR telescope and camera are to be developed over an eight year span, starting in 2009. The facility will be operated to carry out and complete the SASIR Survey in four to five years, starting in 2017. The schedule for the SASIR activities can be summarized in the following schematic phases (Figure 9), with particular aims and terminal points:

1. **Project Establishment (2009):** a) Establish the Project Office and structure, including Project Manager, Project Scientist, Science Advisory Committee and Legal and Environmental Issues Panel b) Define the scientific requirements. Terminates in Project Definition Review.
2. **Conceptual Design (2010–2011):** a) Perform trade studies on cost, schedule, organization, performance and use; characterize the elements that will ensure delivery of the project requirements; Develop a Survey Operations Simulator; Select the final concept for the system identifying possible rescopes. b) Produce a Conceptual Design Document, a System Requirements Document, a Management Plan, a System Engineering Plan, c) develop the Data Management architecture. Terminates in System Conceptual Design Review.
3. **Detailed Design (2012–2013):** a) Perform detailed designs to meet System Requirements, b) Produce a Design Document, an Instrument Allocated Baseline with technical specifications, a complete 3D model and assembly diagrams, an Error Budget Document for mechanical parameters, and a Design Review Document. Terminates in Critical Design Review.
4. **Project Construction (2014–2016):** Construction of the SASIR camera, telescope, building, optics, control system. Terminates in Operation Review
5. **SASIR Survey (2017–2021) and wrap-up activities (2022).** SASIR Survey operations, including science meetings, postdoctoral positions, data archiving, data releases and outreach and extension activities. Terminating in SASIR End Review

In the actual detailed project calendars, the above phases for different subsystems or activities overlap in an out-of-phase fashion. In particular, the project has decided not to develop a completely new telescope concept, but to start from the Magellan or MMT telescope concept, in order to concentrate efforts on new challenges like the camera concept. In particular, the primary mirror has already been secured and is in the process of manufacturing. A more complete breakdown of the activities in these phases is given in the costing chart (§7).

Data for US Scientists: The SASIR collaboration expects to release SASIR survey data to the US and Mexican astronomy communities incrementally during the science operations (following the models of 2MASS, SDSS, UKIDSS), with no more than a 18–20 month delay. Following the LSST model, transients will be released to the US and Mexico community at least as quickly as everyday, and possibly in near real-time.

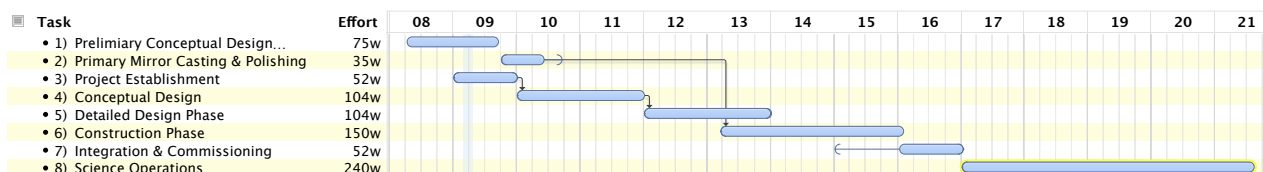


Figure 9 Nominal SASIR schedule assuming ideal funding profile. See Figure 10 for cost details.

Table 2. SASIR Telescope Key Parameters to be Studied

Aspect	Range to be Study	Main Questions/Issues to resolve
Field of View (FoV)	0.5°–1.5°	Science impact (survey speed). Cost and feasibility implications to M1/M2, camera optics & detectors.
Filter Set	YJHK – JHK – YJH	Science impact vs. technical feasibility and costs.
Survey Length	3–9 yrs	Science-Impact/Running-Cost ratio.
Telescope Concept	2-mirror, 3-mirror w/wo re-imaging	Multi-band capability. K-emissivity. FoV. Optics complexity, size and feasibility. Scalability of known reference systems (risk/critical-path mitigation)
Multiple-Filter Strategy	Beam/Field splitting	Impact to base structural design (Magellan). Science impact (band simultaneity). FoV. Performance, cost and feasibility of overall design.
Pixel Size	10–20 μm	Design merits versus camera complexity and cost. Detector development status and costs.
Detector Scale	0.2–0.4"/pixel	Optimization of image-quality budget and sampling, sky background, system dimensions and performance.
Primary Conic Constant	0.9–1.1	M1 figuring. FoV. Image quality. Subsystems simplification.
Focal reducer Collimated Stage	With or without Partial & Complete Refractive & Reflective optics Uncollimated systems	Baffling complexity. Multi-band capabilities. K-emissivity (white pupil). Multi-band capabilities (dichroic requirements). System complexity, performance & feasibility. Classic/Gregorian M2 relation to collimator simplicity.
Focal Station(s)	Cassegrain, Nasmyth	Weight & envelope limitations. Multiband capabilities. FoV.
Atmospheric Dispersion Corrector	Prime foci location	Impact and potential modifications of Magellan design. Necessity for science programs, weight limitations

6.1 Conceptual Design Phase Considerations

Upon securing funding for design work, we will initiate trade studies on cost, risk, and performance for various designs. Early work will concentrate on identifying and retiring the highest technical and cost risk areas. A second high-priority activity will be to clearly identify possible rescopes of the current SASIR concept as part of technical/cost risk mitigation. Table 2 summarizes some of the key issues to be analyzed during the definition phase of the SASIR telescope.

Survey Operations Simulations: In order to assess both telescope design decisions and potential observing cadences on SASIR’s ability to deliver the science, a SASIR Operations Simulator will be developed. The Simulator will accurately reflect telescope performance and capabilities modeling all moving parts. It will utilize available data to model weather and seeing. Finally, it will be able to incorporate a variety of science programs with different goals and cadences. The results of the simulation will be put in a database for ease of postprocessing. Extensive multi-year simulations will allow us to assess the potential output assuming a variety of design decisions and optimize scientific programs so that the multiple program goals can be attained over the course of the survey.

7 Cost Estimates

Aside from having decided on a 6.5 meter honeycomb primary aperture, whose casting process has been initiated at the Arizona Mirror Lab, and a concept for telescope structure and building based on the Magellan/MMT facilities, the SASIR design is at a preconception level. As SASIR is at the early phase of establishing the project, no professional costing activity has been conducted. As hereafter detailed, the present SASIR budget estimate of \$170 Million (FY2009, without contingency nor after-survey operations or instrumentation), running from 2009 to 2022, is partially based on the actual cost of the Magellan telescopes and complemented with our best knowledge of present-day costs for the required subsystems together with the expected management and qualified labor needed. The primary mirror itself has been secured through a partnership between INAOE and the University of Arizona and its cost is already covered.

	Total	Cash Flow (year 1 to 15) Millions of USD (FY2009)														
		2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
PRECONCEPT AND FEASIBILITY STUDY	0.25	0.25														
PROJECT DESIGN & ESTABLISHMENT	0.30	0.03	0.12													
SCIENCE	0.20	0.10	0.05	0.05												
MANAGEMENT	1.80	0.12	0.24	0.24	0.24	0.24	0.24	0.24	0.24							
SYSTEM ENGINEERING	0.85	0.05	0.10	0.15	0.10	0.15	0.10	0.10	0.10							
CIVIL ENGINEERING (Dome & Building)	19.45		0.90	2.65	4.40	5.55	4.23	1.48	0.24							
TEL. MECHANICS (Design, Construction, Integration)	10.39	0.05	0.68	0.28	2.19	2.95	1.93	0.88	1.45							
TEL. & WFC OPTICS (Design, Manufacture, Integration)	21.55	0.26	1.52	0.35	2.90	4.65	5.84	4.83	1.21							
COATING & AUXILIARY SERVICES	5.00				0.75	2.00	1.50	0.50	0.25							
TELESCOPE CONTROL SYSTEM	2.35		0.08	0.18	0.33	0.43	0.65	0.48	0.23							
SASIR CAMERA (Design, Manufacture, Integration)	50.23	0.08	0.15	0.73	5.53	7.85	10.00	9.65	16.25							
SASIR SURVEY	28.15								1.28	4.77	4.72	4.77	4.72	4.77	1.63	1.53
WFST (2nd-Phase Instrumentation)	29.18								0.86	6.10	5.49	4.98	5.23	5.23	1.31	
TOTAL 15-yr PROJECT	169.70	0.93	3.86	4.75	16.43	23.82	24.49	18.15	22.09	10.87	10.20	9.74	9.94	9.99	2.93	1.53
Contingency (15%)	25.45	0.14	0.58	0.71	2.46	3.57	3.67	2.72	3.31	1.63	1.53	1.46	1.49	1.50	0.44	0.23
TOTAL with 15% Contingency	195.15	1.07	4.44	5.46	18.89	27.39	28.16	20.87	25.40	12.50	11.73	11.20	11.43	11.49	3.37	1.75
Project Phase		PROJECT DEFINITION			PROJECT CONSTRUCTION					SCIENCE OPERATIONS (& 2nd-Phase Instr)						
Financial Sources:		NSF, CONACyT & UC, UNAM, INAOE			Private, Federal & Partner Univs.					Federal, Private & Partnership Institutions						

Figure 10 Nominal costing cash flow organized in work packages.

Camera:

The cost and lead time of the detectors and the readout electronics are well understood, with nominal costs (without contingencies) for 124 + 10 spare arrays of <\$35M. This price makes use of the “buy the distribution” notion, where, for instance, lower quality (e.g. higher dark current) arrays from a foundry run would be used in the K -band channel (which has a larger contribution from the sky). Price per pixel is expected to drop by more than a factor of 2 if the 4k x 4k lines become well established in the next few years.

With the lack of a more advanced design for this very important component, the cost of the NIR SASIR Camera is only indicative, and we consider its costing as the least reliable estimate in the present budget. Although the LSST camera is not a strictly applicable reference, nevertheless there are several reasons to expect the SASIR camera to be less costly: 1) there are no moving parts inside the camera; 2) the FoV is significantly smaller with a smaller aperture telescope; 3) the SASIR detector planes are each three times smaller; 4) the field corrector is not part of the camera and has much smaller optics. Relative to other NIR imaging projects (e.g., VISTA, UKIDSS), SASIR is unique in considering four independent focal planes, avoiding the need for filter-change mechanisms and permitting optics and detector cost-saving optimizations with wavelength. In particular, SASIR detectors will likely be fabricated to be insensitive beyond $1.8 \mu\text{m}$ for the Y , J , and H arms, therefore requiring costly thermal-background blocking and a cold-pupil solely in one arm (K).

Table 3. SASIR Costing Organized by Phases [“Federal” component is assumed to be an equal split between US and Mexican national funding agencies]

		Nominal US National Share
PROJECT ESTABLISHMENT (1yr):	0.77	0.19
Federal (50%) and Institutional (50%) Funds		
SASIR Science Case & Survey Definition	0.20	
Project Office, Manager & Scientist	0.32	
Project Concept & Feasibility Study	0.25	
CONCEPTUAL DESIGN (2yr):	3.26	1.47
Federal (90%) and Institutional (10%) Funds		
Project/Consortium Design & Establishment	0.30	
Telescope Structure & Dome PD	0.35	
Wide-field Telescope Optical PD	0.30	
SASIR NIR Camera PD	0.35	
Survey & Operations PD	0.03	
PDR	0.05	
Management & PO Labor	1.88	
DETAILED DESIGN (2yr):	3.37	1.52
Federal (90%), Institutional (5%) and Private (5%) Funds		
Telescope Structure, Dome & Mechanisms DD	0.30	
WF-telescope Global Configuration & Optical DD	0.54	
SASIR Camera DD	0.50	
Dynamical and Kinematical models	0.05	
Survey & Operations DD	0.05	
CDR	0.05	
Management & PO Labor	1.88	
CONSTRUCTION (3yr):	104.97	0
Federal (25%), Private (70%) and Institutional (5%) Funds (Mexico only)		
Civil Work	23.85	
Site Development and Main Infrastructures	7.50	
Building and Dome	10.00	
Aux. Services: Cables/Hoses, Support Elements, Supplies	0.90	
Coating Facility & Auxiliary Optical Services	5	
PO Labor (equiv. to 2 engineers over 3 years)	0.45	
Telescope Structure & Mechanism Construction	9.05	
Structure and Mechanisms Manufacturing	8.00	
Structure and Mechanisms Integration	0.25	
Struc., Mechanisms & Subsystems Acceptance Tests	0.10	
Structure & Subsystems Alignment	0.15	

Table 3—Continued

		Nominal US National Share
Global Acceptance Tests	0.10	
PO Labor (equiv. to 2 engineers over 3 years)	0.45	
Telescope & Wide-Field Correcting Optics	20.08	
(Manufacture & Integration)		
Primary Mirror	10.00	
Secondary Mirror	2.50	
Calibration & Guiding Services	0.40	
Wide-Field Corrector & other (TBC) optics	4.60	
Global Alignment	0.20	
PO Labor (equivalent to 2 engineers over 2.5 years)	0.38	
Telescope Control System	2.35	
Hardware and Software	1.00	
PO Labor (equivalent to 6 engineers over 3 years)	1.35	
SASIR Camera Manufacture & Integration	48.63	
Optical components	10.50	
Structure, Mechanisms & their Control	1.00	
Cryogenics & Control	1.50	
Detectors & Control	33.00	
Camera Integration	0.20	
Camera/Telescope Integration	0.05	
Pipelines and Survey Software	2.00	
PO Labor (equivalent to 2 engineers over 2.5 years)	0.38	
Project Management & System Engineering	1.02	
SASIR SURVEY (4–5yr):	28.15	12.67
Federal (90%), Private (5%) and Institutional (5%) funds		
On site operations (5 yrs)	15.00	
Data Transfer, Processing, Management & Storage	3.70	
Post-Doctoral Positions (5 during 8 years)	3.00	
Postgraduate Fellowships (10 during 6 yrs)	3.20	
Science Workshops	0.20	
Extension Activities	2.00	
PO Labor (equiv. to 2 engineers over 7 years)	1.05	
2nd-Phase INSTRUMENTATION	TBD	
2nd-Phase OPERATIONS	TBD	
PROJECT DISMANTLING	TBD	

Glossary

2MASS	Two-Micron All-Sky Survey	1
AGN	Active Galactic Nuclei	2
BD	Brown Dwarf	1
BH	Black hole	2
CDR	Conceptual Design Review	15
CONACyT	Consejo Nacional de Ciencia y Tecnología	12
DD	Detailed Design	15
EM	Electromagnetic	4
FOV	Field of View	14
GSMT	Giant Segmented Mirror Telescope	1
GW	Gravitational wave	4
IA-UNAM	Instituto de Astronomía at Universidad Nacional Autónoma de México	12
INAOE	Instituto Nacional de Astrofísica, Óptica y Electrónica	12
IR	Infrared	1
JWST	James Webb Space Telescope	1
NIR	Near-IR	1
NSF	National Science Foundation	12
OAN	Observatorio Astronómico Nacional	10
ODI	One-Degree Imager	15
P-L	Period-Luminosity	3
PD	Preliminary Design	15
QSO	Quasi-stellar Object	2
RATIR	Reionization and Transients Infrared Project	1
SDSS	Sloan Digital Sky Survey	2
SNe	Supernovae	3
SPM	San Pedro Mártir	1
TMT	Thirty Meter Telescope	9
UKIDSS	United Kingdom Infrared Deep Sky Survey	1
UV	Ultraviolet	2
VISTA	Visible and Infrared Survey Telescope for Astronomy	2
WISE	Wide-Field Infrared Survey Explorer	1
WP	Astro2010 Whitepaper	1

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