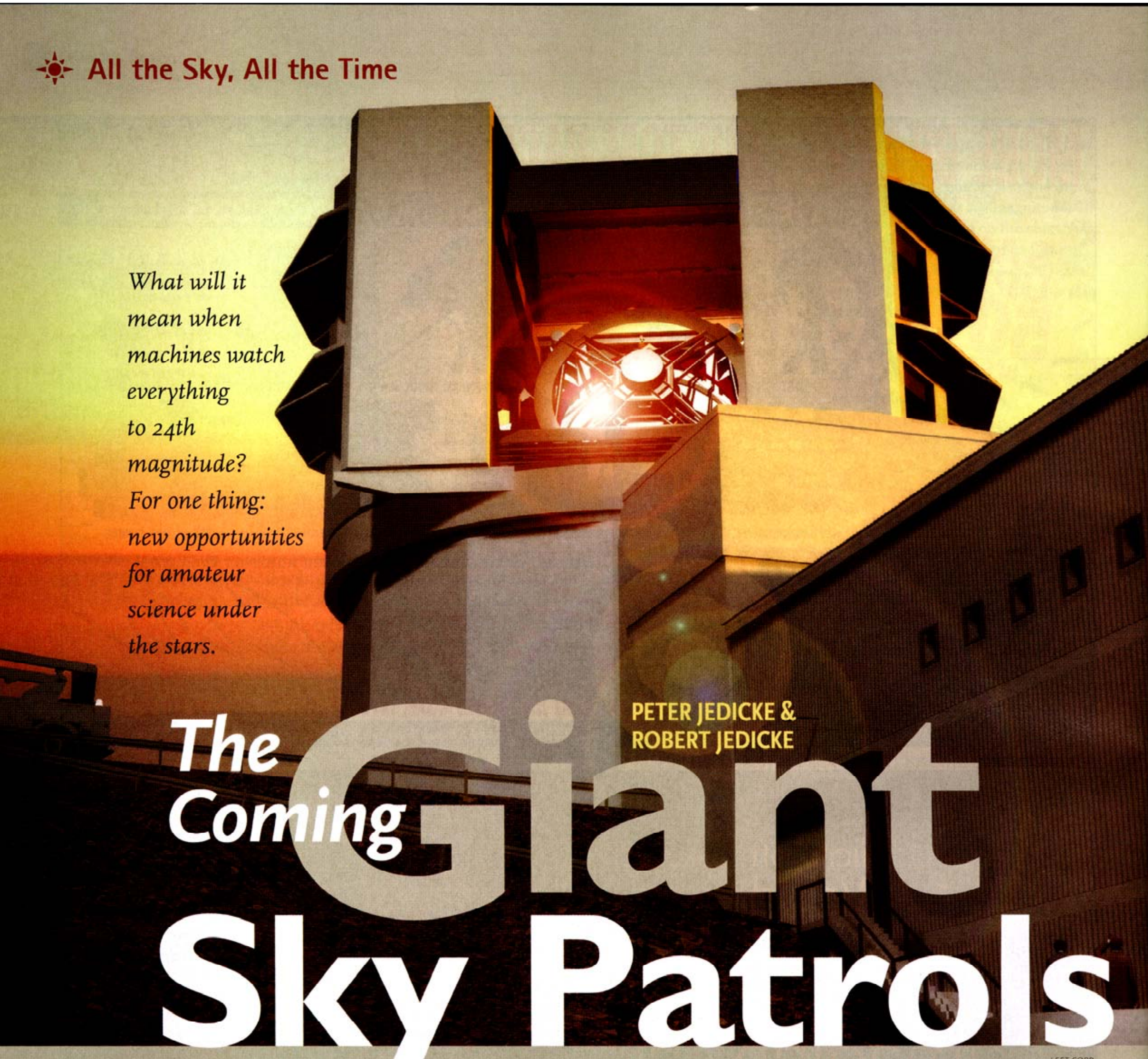


LSST CORP

The Coming Giant Sky Patrols

What will it mean when machines watch everything to 24th magnitude? For one thing: new opportunities for amateur science under the stars.

PETER JEDICKE & ROBERT JEDICKE

ALL-SEEING EYE Starting around 2016, if all goes as planned, the 8.4-meter Large Synoptic Survey Telescope (LSST) should be watching everything in its sky to about magnitude 24.5.

THE PACE OF astronomical discovery is about to take a big leap up, and stay there. A new generation of sky-patrol telescopes and cameras will soon be monitoring the universe with awesome comprehensiveness — combining big apertures, wide fields, massive data rates, and machine intelligence to do things that human astronomers cannot.

Anyone with an Internet connection will have ready access to stupendous amounts of archived, and freshly incoming, data unseen by human eyes. The coming sky surveys will harvest almost every transient or moving target that we consider worth discovering — from small, potentially hazardous asteroids near Earth to supernovae at cosmological distances. The biggest of the upcoming surveys will issue an estimated 10,000 alerts per night about interesting things happening that need following up.

Perhaps the big question in 2020 will be: is there anything left unseen?

Taking the Wide View

There's nothing new about surveying the sky. Astronomers as far back as Hipparchus (around 130 BC) cataloged stars to have a reference for future observations. William Herschel may have been the first to do a telescopic all-sky survey; he intended to sweep up everything his 7-foot-focal-length reflector could show. The power of this approach became apparent when, in 1781, he discovered Uranus. By contrast, we know from Galileo's manuscripts that Galileo *missed* discovering Neptune some 170 years earlier because he was studying a specific object — Jupiter — and didn't check what might be happening in its vicinity.

A century ago, the ambitious Carte du Ciel project attempted to record the whole sky on photographic plates. The Palomar Observatory Sky Survey finally succeeded at this endeavor in the 1950s, providing a resource that changed astronomy forever.

In the visible wavelength range, the state of the art today is the Sloan Digital Sky Survey (SDSS), which logged 215 million celestial objects in its first phase, SDSS-I. (The second, SDSS-II, is just now wrapping up.) Among its finds were more than 500 Type Ia supernovae and nine very sparse dwarf galaxies that are near or merging with the Milky Way. Astronomers found these loose stellar groupings by sorting their individual stars' characteristics and motions out of the masses of data.

But when SDSS-I ended in 2005, it had surveyed only one-fifth of the sky — and only once. The next-generation surveys will image the entire night sky that's visible from their locations over and over again, every few days.

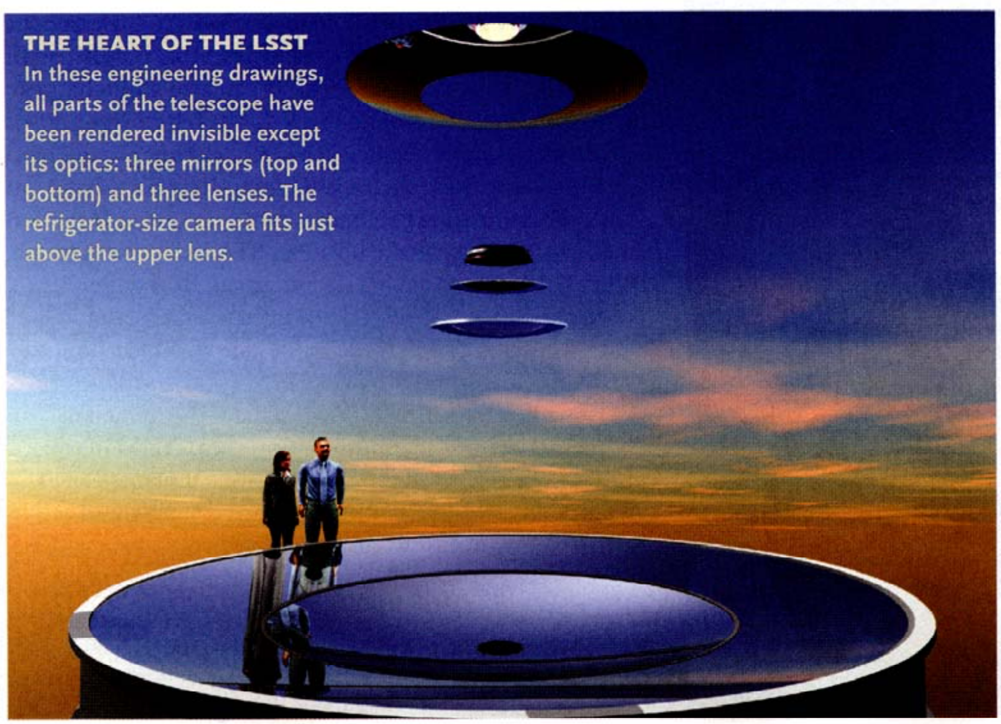
Giants on the Horizon

The project closest to completion is the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), which should be up and running in a few months. Even bigger will be the Large Synoptic Survey Telescope (LSST), which should start work in 2016 if its funding continues on track. Others under construction include the VLT Survey Telescope (VST), the Discovery Channel Telescope (DCT), and SkyMapper. The European Southern Observatory is building a 4.1-meter survey telescope called VISTA optimized for near-infrared wavelengths.

Well-known older and current programs such as Spacewatch, the Lincoln Near Earth Asteroid Research (LINEAR) project, the Catalina Sky Survey (CSS), the Lowell Observatory Near-Earth-Object Search (LONEOS), and NASA's Near-Earth Asteroid Tracking program (NEAT) will soon be superseded, despite their frequent upgrades.

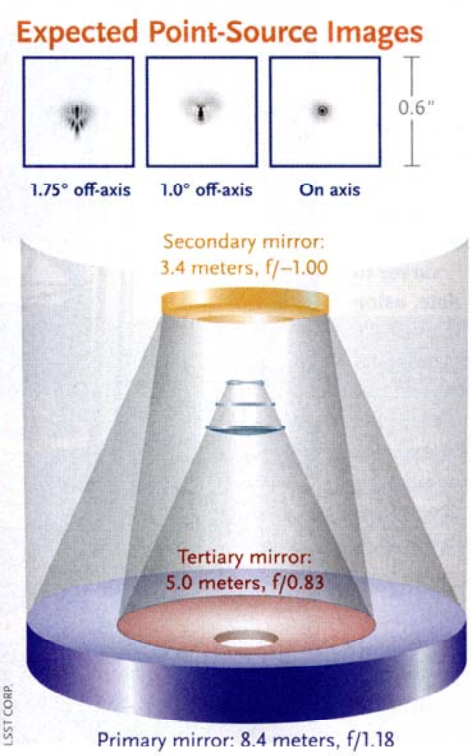
Every new large observatory, whatever its mission, is built around some combination of recent major technical developments. These include thinner mirrors to reduce mass and cost, short-focal-length primary mirrors that couldn't be figured precisely until recently, segmented mirrors that allow big apertures impossible for a one-piece mirror, and dome designs born in wind-tunnel studies that minimize image-degrading turbulence.

Perhaps most significant are *active optics*, mechanisms that compensate for the bending of thin mirrors due to mechanical loading and temperature changes, and *adaptive optics*, which react hundreds of times per second to cancel out the ripplings and blurrings of images caused by Earth's



THE HEART OF THE LSST In these engineering drawings, all parts of the telescope have been rendered invisible except its optics: three mirrors (top and bottom) and three lenses. The refrigerator-size camera fits just above the upper lens.

LSST CORP.



S&T: CASEY REID

atmosphere. When cost and engineering challenges are considered, modern ground-based observatories compete head-on even with the Hubble Space Telescope.

LSST: The Future King

Advances in wide-field optical design, detector technology, and data handling are enabling the new survey telescopes. The heart of the LSST, for instance, is a single glass disk 8.4 meters across with two optical zones. The outer ring constitutes the f/1.18 primary mirror, and the inner zone is the f/0.83 tertiary (see previous page). The convex secondary will be 3.4 meters across, the largest convex telescope mirror ever made.

After three reflections, the incoming light goes through three big lenses, the largest of which is 55% larger than the objective of the venerable 40-inch Yerkes telescope, the world's largest refractor. Such sophisticated optical designs could not even have been developed, much less manufactured, a generation ago. The payoff for LSST will be an image plane that is flat and optically superb (pinpoint star images, with aberrations smaller than 0.2 arcsecond) across a sky-hungry 3.5°.

To record this wide field, LSST will incorporate the world's largest digital camera — bigger than a refrigerator, with 3.2 billion pixels. In three clear nights, LSST will routinely image the entire vault of the heavens above it to magnitude 24.5.

And that's with the planned exposures just 15 seconds long. LSST will go deeper if its handlers decide to trade occasional longer exposures for reduced sky coverage.

LSST CORP.

BIG PICTURE The heart of the LSST will be a 3,200-megapixel CCD array. On this mockup, the full Moon (about ½° wide) illustrates the image scale on the sky. Image sensors in the corners will handle guiding and tracking.

INSTITUTE FOR ASTRONOMY

ALREADY UP AND RUNNING Pan-STARRs 1, a 1.8-meter survey telescope on the summit of Haleakala in Hawaii, is finishing its shakedown and will soon commence the most powerful sky survey to date, using the world's largest digital camera. But it's just the prototype for the four-telescope Pan-STARRS 4.

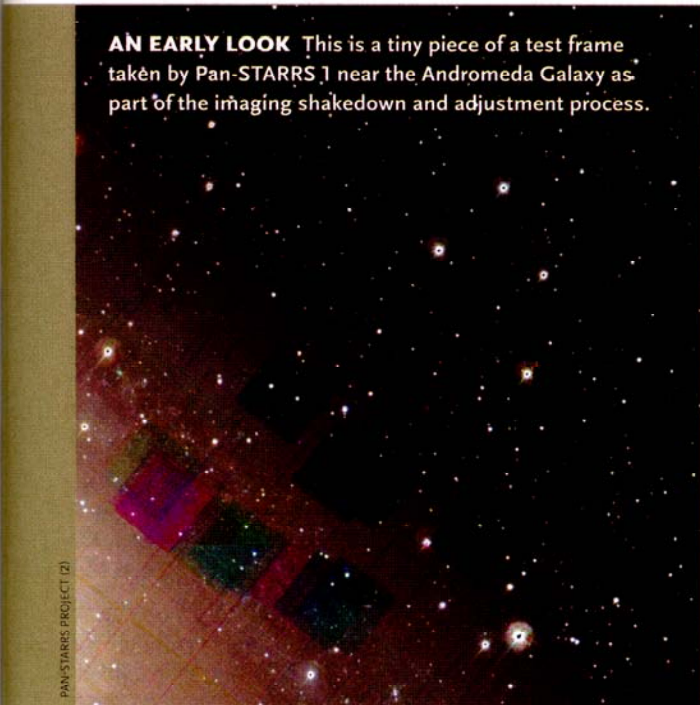
Pan-STARRS: Arriving Shortly

Pan-STARRS takes a different, and ultimately less costly, approach to achieve fairly similar performance. A prototype 1.8-meter telescope is already sucking down photons atop Haleakala, the volcanic peak on the Hawaiian island of Maui. It should finish its shakedown and begin regular work within months. PS1, as it's called, also has a compound optical design with a convex secondary mirror and three corrective lenses in front of a large, flat image plane.

The unique feature of Pan-STARRS is its CCD detector-chip array and readout. The detectors are "orthogonal transfer" CCDs (OTCCDs), invented by John Tonry and others at the University of Hawaii's Institute for Astronomy and MIT's Lincoln Laboratory. Like all CCD cameras, an OTCCD reads out the electric charge that builds up as light strikes a pixel. An OTCCD can also shift charges around on the chip — onto pixels to the left or right, up or down — even while the exposure is taking place. This allows the camera to do tricks of image tracking that would be impossible mechanically.

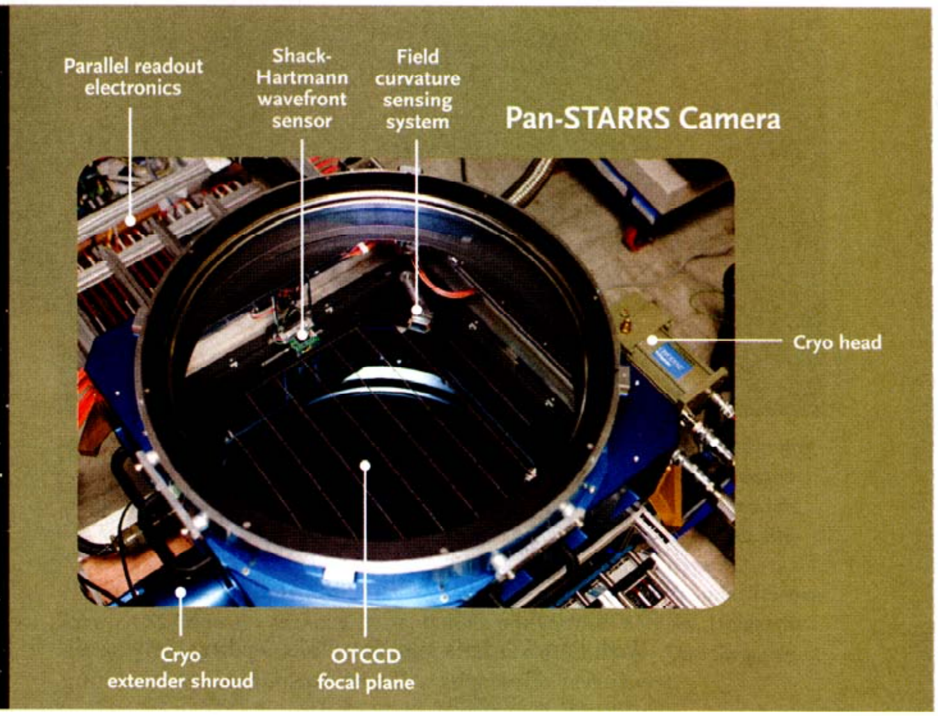
Sixty such chips make up a Pan-STARRS camera frame, about 32 cm (1 foot) square (facing page). By monitoring the images of a guide star in the frame, and shifting charges to other pixels as the guide star meanders around for whatever reason (such as atmospheric disturbance or mechanical shakes), the OTCCD follows the motion of every object while the exposure continues. Preliminary results show that this innovation shrinks the image of a point source by 20% or more compared to standard imaging. The incoming light is thus concentrated on 36% fewer pixels, enabling the system to detect fainter point sources. In addition to having no moving parts, an OTCCD compensates for each part of an image across a wide field, something conventional adaptive optics can't do.

The Pan-STARRs project is building four new tele-



AN EARLY LOOK This is a tiny piece of a test frame taken by Pan-STARRS 1 near the Andromeda Galaxy as part of the imaging shakedown and adjustment process.

PAN-STARRS PROJECT (2)



scopes nearly identical to the PS1 prototype; they will yield a combined aperture equivalent to 3.6 meters. The preferred location for PS4, as this observatory will be known, is the site of an old dome on Mauna Kea. Although cost is certainly one reason in favor of four mirrors instead of a single big glass eye, an additional benefit is that multiple images can cross-check each other, eliminating such nuisances as cosmic-ray hits and imperfections in the CCD chips. The flexibility of having four telescopes is also an advantage: data can be gathered through different color filters simultaneously, for instance.

SkyMapper, VST, DSC

Coming close behind PS1 will be SkyMapper, located in the Southern Hemisphere. It is similar to PS1 (and is being built by the same commercial optical team in Tucson), but it's somewhat smaller, with a 1.35-meter primary mirror.

Soon after SkyMapper, a 2.6-meter instrument will see first light adjacent to the four 8.2-meter behemoths of the European Southern Observatory's Very Large Telescope (VLT). Called the VLT Survey Telescope (VST), it will tell astronomers about things it catches that are worthy of a deeper look.

Rounding out the new projects is the Discovery Channel Telescope (DCT) in northern Arizona, which will have a larger aperture at 4.2 meters. The DCT will not be a survey telescope when it sees first light in 2010, but its builders hope to add a wide-field camera later on.

How Productive?

To compare these telescopes, researchers use a rating called *étendue,* French for "extent." It's a simple formula:

Death of Amateur Astronomy . . . or New Birth?

Generations of amateurs were raised on the hope of doing real science by discovering a comet over the neighbors' rooftops or judging variable stars by eye in the eyepiece. So amateurs have viewed the coming giant sky patrols with mixed feelings. Will there be any useful astronomy left for amateurs to do?

Absolutely, says LSST project director Anthony Tyson (University of California at Davis). He is counting on well-equipped amateurs to play a role in following up LSST's fresh observations. Someone has to check up on the many surprise happenings it will flag every night. And the giant camera will be partly hobbled by its own power: seeing as deep as magnitude 24 means it can't measure things brighter than about magnitude 16. That's where an amateur with a typical CCD camera on a good backyard scope can take over.

"We will find many objects on the rise, with alerts within 60 seconds," says Tyson. "It's a new sky that will be opening, and amateurs will be able to share with that. It's a different game, and it'll be more fun."

— *Alan MacRobert*

LSST CORP. (3)

PAST, PRESENT, FUTURE
Left: This is a tiny bit of sky in the photographic Palomar Observatory Sky Survey. *Middle:* The Sloan Digital Sky Survey goes deeper, sharper, and records five colors. *Right:* The recent Deep Lens Survey was only a partial step toward what will come with the giant sky patrols of the future.

multiply the light-collecting area of the telescope (in square meters) by the area of the useful field of view (in square degrees). *Étendue* measures a telescope's potential sky-survey effectiveness. A large aperture can probe more quickly for dim discoveries; a wide field lets the telescope swallow more sky at once. With most telescopes designs, you can have one or the other. A survey telescope tries to maximize both.

With Pan-STARRs and later LSST leading the way, the new survey telescopes will have *étendue* values exceeding anything before (see the table below.) As a comparison, if a university, or a sky's-the-limit amateur, spent $50,000 for a 16-inch f/3.6 astrograph with a top-of-the-line wide-field CCD camera — gear that's currently on the market — the setup would have an *étendue* of 0.3. By comparison, the value for the LSST will be about 1,000 times greater.

For much more about the visible-light sky surveys of the present and future, go to SkyandTelescope.com/SkySurveys.

What We'll See

The science goals of the new survey telescopes would make Herschel whistle. In 2005, Congress directed NASA to find 90% of Earth-approaching asteroids larger than 140 meters — those that could inflict regional devastation if they ever struck our planet — by 2020. LSST could achieve this goal within about eight years of full-scale operation. It'll also inventory vast numbers of other asteroids, icy objects beyond Neptune, and otherwise undiscoverable comets.

Beyond the solar system, Pan-STARRs and LSST will make enormous, detailed catalogs of deep-sky objects with uniform image characteristics. By frequently reimaging much of the celestial sphere, astronomers will discover and track vast numbers of variable stars, microlensing events, exoplanet transits across stars, nearby dim dwarfs with high proper motions, faint optical bursts, supernovae in very distant galaxies, and, no doubt, unexpected surprises. Monitoring almost every type of astronomical target on a continuing basis will establish a new kind of vigilance for

Sky Surveys and Their Effectiveness

	LSST	Pan-STARRS (PS4)	DCT	VST	Pan-STARRS (PS1)	SkyMapper	SDSS-I
Location	Cerro Pachón, northern Chile	Mauna Kea, HI	southeast of Flagstaff, AZ	Paranal, Chile	Haleakala, HI	Siding Spring Obs., Australia	Apache Point Obs., New Mexico
Start date (expected)	2016	2011	2010	spring 2009	late 2008	2007	2000
Primary aperture (m)	8.4	3.6 (4 × 1.8)	4.2	2.6	1.8	1.33	2.5
Field of view (sq. deg)*	9.6	7.1	3.1	0.6	7.1	5.7	1.5
Étendue (m × sq. deg)**	320	51	39	2.7	13	5.6	6.0
Limiting magnitude***	24.5	24	24		22.7	21.2 (g)	23.1
Colors (filters)	u g r i z Y	g r i z Y	B V R I W****	Z Y J H K_s N B1.18	g r i z Y	u v_s g r i z	u g r i z
Revisits per field per night	42	4	2	6	5	4	5
Square degrees per night	8,000	6,000	4,000		6,000	1,500	750

* The instrumented field-of-view area, whenever possible.
*** Approximate limiting magnitude is in terms of the SDSS r' filter whenever possible.
** Based on the clear aperture, correcting for obscuration by the secondary mirror.
**** W is a wide-band "white" filter essentially equivalent to B+V+R.

humanity, an archived newsreel of the universe.

Although spectrometers are not part of the survey telescopes, Pan-STARRs and LSST will use four of the wavelength filters SDSS used, called *g, r, i,* and *z,* and a fifth named *Y:* these are standardized green, red, and three colors in the very near infrared. For galaxies, these five colors will allow LSST and Pan-STARRs to determine "photometric redshifts." These are less accurate than redshifts found by measuring individual spectral lines, but they can be determined in bulk. By comparing model galaxy spectra to galaxies observed through the *grizY* filters, vast numbers of redshifts will be collected, improving 3-D maps of the large-scale structure of the universe — and hence our knowledge of dark matter and dark energy.

Each raw Pan-STARRs image requires about 3 gigabytes of disk storage. Pan-STARRs will take an image every 30 seconds, producing several terabytes of data per night. The PS1 telescope alone will require tens of petabytes (tens of millions of gigabytes) of storage for its currently planned project. Analyzing the data as it's obtained will push the limits of today's computer technology; all the surveys will use massively parallel systems of processors.

Astronomy's Changing Future

The ultimate question is whether there will be anything left to discover. Once the entire sky is being imaged to 24th magnitude every three nights by LSST and Pan-STARRS, almost nothing will be left for discovery by amateurs. Will future amateur astronomers just sit at screens, mining data online?

CSS	LINEAR	Spacewatch	8-inch f/10 scope
Mt. Lemmon, AZ	New Mexico	Kitt Peak, AZ	Your backyard
1998	1998	1984	
1.5	1	0.9	0.2
1.2	2.0	2.9	0.66
2.0	1.2	1.6	0.02
21.5	19.5	21.5 (V)	18 (CCD)
none	none	og515	
3			
600	2000	300	


DAVID HARVEY / LSST CORP.

MIRROR TAKES SHAPE The 8.4-meter LSST mirror was cast in the spinning oven at the University of Arizona's Stewart Observatory Mirror Lab in Tucson. "High fire" in the oven (the maximum planned temperature) was reached late last March, with LSST dignitaries celebrating. The oven's rotation shapes the molten glass into a paraboloid. (See the loading of the glass on page 77.) *Left to right:* Mirror Lab director Roger Angel, Steven Beering (National Science Board), LSST director Anthony Tyson, Purdue physicist Ian Shipsey, University of Chicago cosmologist Rocky Kolb, and LSST project manager Don Sweeney.

Some surely will. Pan-STARRs will hold its data back for a proprietary period before releasing it, but LSST plans to put everything on the Internet essentially in real time. As amateur discoverers working with the SOHO solar observatory and the Puckett Observatory Supernova Search already know, data-watching is a fruitful approach.

But LSST director Anthony Tyson foresees exciting times for outdoor, under-the-stars amateurs hoping to do frontline science with their telescopes. He expects LSST to issue "upwards of 10,000" nightly alerts of possibly interesting events. Most won't amount to much — but someone should check. And when a brightening object rises above magnitude 16, it will become too bright for LSST to measure. That's where CCD-equipped amateurs can take over (see sidebar on page 33).

Well before then, the other new sky surveys should already prompt a new wave of amateur-professional collaboration. To follow up on every new variable star, supernova, comet, or asteroid would require more than all the professional telescopes in the world. Yes, traditional amateur doors to discovery are closing. But more are opening up. ✦

Peter Jedicke *teaches at Fanshawe College in London, Ontario. He was president of the Royal Astronomical Society of Canada in 2004–06 and wrote "A Boy and His Telescope" in* Sky & Telescope *for September 1992.*

Robert Jedicke *has had careers as a pro football player, particle physicist, software engineer, and astronomer. He is currently manager of the Pan-STARRS Moving Object Processing System, which will discover more asteroids and comets each month than have been found in the past two centuries.*