CTIO Dark Energy Camera Meeting
Fermilab- Dec 5 and 6

The Dark Energy Camera
Draft Science Requirement Flowdown

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1.1 Introduction

The Dark Energy Cosmography Project aims to make precision measurements of dark energy through wide area sky surveys. We will do this by designing an experiment to measure the photometric redshift of clusters of galaxies out to z=1 over a 5000 square degree area of the Southern Galactic Cap. This area is chosen to overlap the high resolution map of the CMB produced by the South Pole Telescope. These data allow us to probe dark energy in several ways:

- Clusters of galaxies
- Weak lensing power spectra and cross-correlation cosmography
- CMB and galaxy/cluster/shear cross-correlations

The primary requirements are set from the cluster program, while the weak lensing and CMB cross correlations programs, given the context of the cluster program, provide secondary requirements.

1.1.1 Clusters of Galaxies

There will be cluster catalogs built three ways

- from the Sunyaev-Zeldovich map, deepest in z, shallowest in mass
- from the weak lensing shear map, shallowest in z
- from the galaxy magnitudes, deepest in mass

The first 2 catalogs will have their redshifts measured using photometric redshifts of the third catalog.

These catalogs will allow a study of the evolution of the mass function via cluster number evolution along with mass calibrations derived from SZ, shear, and galaxy number estimates and cross checked from the cluster angular power spectrum.

The mass function is sensitive primarily to power spectrum, secondarily to the growth and volume functions. Fortunately, the power spectrum is well constrained from CMB and galaxy distribution large scale structure power spectra. The growth function and volume element are both sensitive to the dark energy equation of state, w, and its time derivative, w'.

1.1.2 Weak Lensing

Both the galaxy distribution and the weak lensing shear distribution measure the matter power spectrum, though the former is biased by the amount that the light from galaxies doesn't trace mass. We will pursue

Flowdown Requirements

- galaxy power spectra in photo-z bins
- weak lensing shear power spectra in photo-z bins
- weak lensing shear cross correlation cosmography (the Jain and Taylor method)

These get at w and w' via the growth of the power spectrum, or through angular diameter distances.

1.1.3 CMB Cross Correlations

Galaxy/cluster/shear correlations with the Cosmic Microwave Background provide a means to test cosmology primarily through the growth function. The CMB data may be either data from the South Pole Telescope, which will produce a 4000 sq-degree survey with 1' resolution, or WMAP (in process) or Plank (2008 launch). The effects of large scale structure on the photons of the CMB are numerous, and there is a rich physics largely untouched by observation on the topic. The SZ is well measured, but only the first detections of ISW are coming out; one can measure w in this way. In fact, Stebbins argues that the ISW at z=1 will primarily be sensitive to w', a very interesting point.

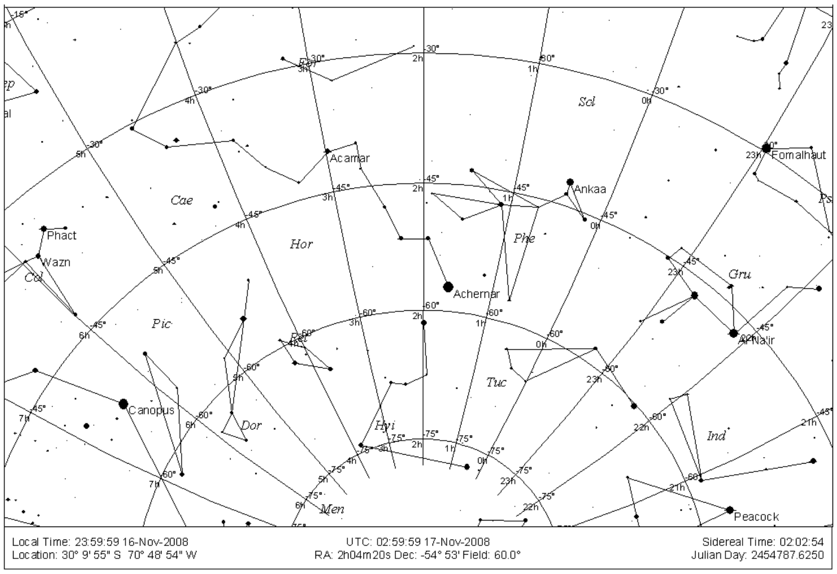

Fig. 1.1. A sky map centered on the survey area.

1.2 Cluster Science Requirements

1.2.1 The Footprint

Figure map shows the area around the South Galactic Pole.

Figure refdirbe shows a strawman footprint. We aim to cover $\geq$ 3000 square degrees of sky area observable from the South Pole, so as to overlap SPT, and to get area overhead of CTIO, so as to cover areas accessible to the CMB telescopes in Chile.

We aim at 5000 sq-degrees.

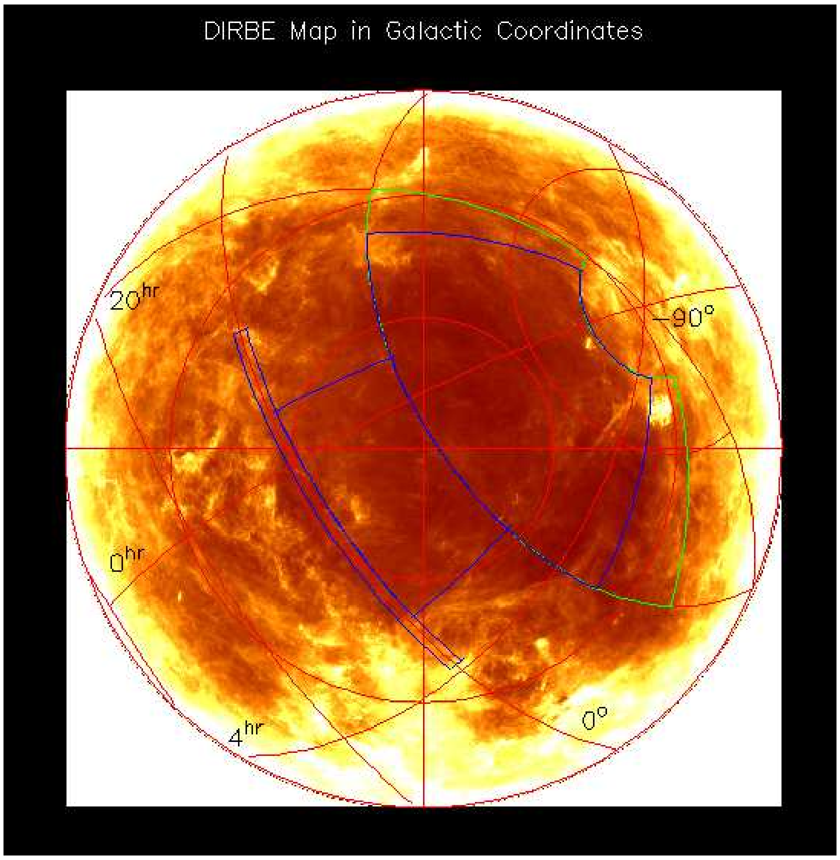

Fig. 1.2. The DIRBE dust map as processed by Schelgel, Finkbeiner and Davis. This lambert equal area project plot is extremely useful. The image is the dust in the Southern Galactic Cap: the South Galactic pole is at plot center, and the galactic disk runs around the edge. The red circles are at -30 and -60 degree galactic latitude. The offset red circles show equatorial coordinates. The South Pole is at upper right, with rings of constant declination at -60, -30, and 0 degrees declination shown. This happens to be an alt-az plot from CTIO on Halloween night at midnight. At that time, the lines of galactic latitude are also lines of airmass. The inner circle is 30 degrees, and hence airmass 1.15. The 60 degree circle is airmass 2. We would prefer to keep all observations to airmass ≤ 1.5, corresponding to 48 degrees from zenith. Lines of equatorial right ascension are shown, marked by hour on the left. The sky moves 2 hours/month at constant time (say, always at midnight), so the alt az graticule will move along the circle of -60 degree declination at 2 hours/month, a useful thing to know to estimate airmass at different times a year. The green lines show the extent of the SPT, which can observe up to 60 degree zenith distance at the South Pole, hence up to -30 declination. The blue lines show strawman footprint, with the southernmost region overlapping the SPT area, the SDSS south equatorial strip (useful for photo-z calibration) as the most northern skinny strip, and a region designed to take the total to 5000 sq-degrees and observable at very low airmass remaining. The current thinking is to move the southernmost area two hours to the east, to take the observing season towards the more favorable summer. This would allow us to use October, November, December, and February for observing.

1.2.2 Limiting Magnitudes

The aim is to achieve good photometric redshifts on massive clusters of galaxies out to $z \approx 1$. Since most of the galaxies in clusters have E/S0 spectra, the problem becomes predicting the magnitudes of ellipticals at $z \approx 1$.

1.2.2.1 J. Mohr

Calculate depth by estimating how deeply we must go to get a minimum of 10 galaxies in a galaxy clusters of limiting mass in the SZ survey at a redshift of z=1. In the local universe the mass to light is a smooth function of mass, and the luminosity function shape parameters $L^\star$ and alpha are constant or weak functions of mass (Lin, Mohr and Stanford ApJ, 2003, and in preparation). Cluster galaxies evolve passively, and so using a redshift z=3 or z=5 burst model we can estimate $L^\star$ as a function of band and redshift from a local normalization using our own data (or redshift z 0.5 normalization using other people's data). This limit roughly corresponds to (Johnson) R=24.5, and tuning the other filters crudely to an elliptical galaxy color, I have chosen the photometric target depths to be griz = 25,24.5,24,23.5, at 10σ.

Limiting magnitudes

filter	g	r	i	z
mag (10σ)	25	24.5	24.0	23.5

Note that these arguments are quite different from Jim's fixed fraction of $L^\star$ arguments. We need to have enough galaxies in every SZ cluster to estimate its redshift, and this means going to different fractions of $L^\star$*, depending on the mass of that cluster.

1.2.2.2 J. Annis

One can obtain cluster catalogs 90% complete and 90% efficient for $M_{cl} \geq 10^{14} M_\odot$ if one has $\geq 10\sigma$ observations of the colors of elliptical galaxies of $\geq 0.5L^\star$. (These numbers are based both on observations of galaxy enhanced N-body simulations and on Monte Carlo additions of clusters into the SDSS data stream.) The resulting cluster catalogs have photo-z uncertainties of $\Delta z \leq 0.02$ for clusters with more than 2-3 galaxies. The mean $10^{14} M_\odot$ cluster has 20 galaxies brighter than $0.5L^\star$.

$L^\star$: Blanton et al (2003) have $M_i^\star = -21.01$ (z=0, evolution corrected). An $0.5L^\star$ galaxy is then $M_i = -20.25$.

What is the corresponding apparent magnitude? This depends both on the cosmology and the spectra of the object. The cosmology assumed is a $\Omega_\lambda = 0.7$, flat, cosmological constant universe. The spectrum is an old elliptical spectra including passive evolution. In figure 1.3 the k+e curves are plotted for the magnitudes, and in figure 1.4 the colors, for $0.5L^\star$ elliptical galaxies. These k+e curves are in SDSS colors, but more to the point, are known to be right for $0 \leq z \leq 0.4$. The curve is the model derived from a Pegase-2 14 billion year old (at z=0) galaxy assuming solar metallicity initial gas infall model, with self consistent metal enrichments, and galactic winds causing cessation of star formation at $z = 3$, and is intentionally quite red so as to match the observations, but which we can take as a worse case. The details of the model are less important than the fact that it provides a convenient fitting function to the data.

We need precision colors, which correspond to a S/N of 10σ in colors and 13σ in magnitudes, though in the SDSS we find 8σ in the magnitude of the blue filter is acceptable if the

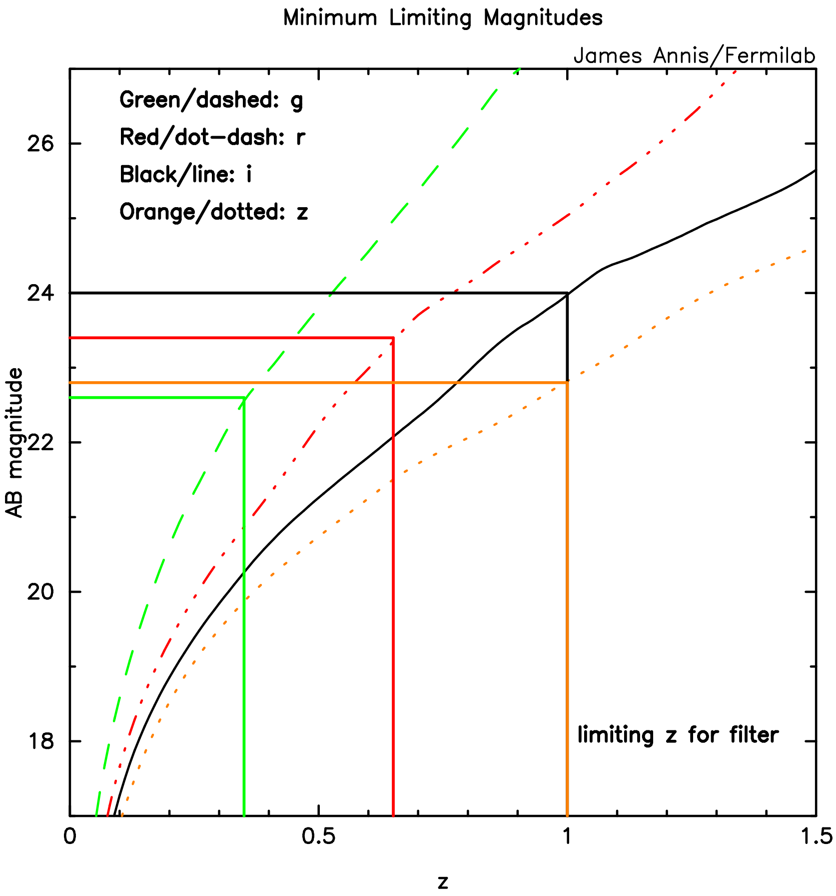

Fig. 1.3. Magnitudes of $0.5L^{\star}$ galaxies in 4 bandpasses. The vertical line gives the redshift at which the 4000 A break leaves the filter, a measure of the limit of which one needs 10σ precision.

red filter is 13σ. The calculation of the signal is then calculation of the expected apparent magnitude of a $M_i = -20.25$ elliptical galaxy at $z = 1$ in the i band.

Limiting magnitudes

filter	g	r	i	z
mag (13σ)	22.8	23.4	24.0	22.9

1.2.3 Wavelength Coverage

The filters must provide a bracketing of the 4000A break signal in the elliptical galaxy spectrum. At z=0, the blue side limit is 400 nm. At z=1, the 4000A break is at 8000A, and we need a filter redward of this. Assuming we adopt the SDSS filter set, this implies the required filters are g, r, i, z We note that objects at z=0 are bright, and at z=1 are dim. The overall system throughput efficiency of g need not be as high as at z. (We further note that the z filter should not be confused with the standard symbol for redshift, z.)

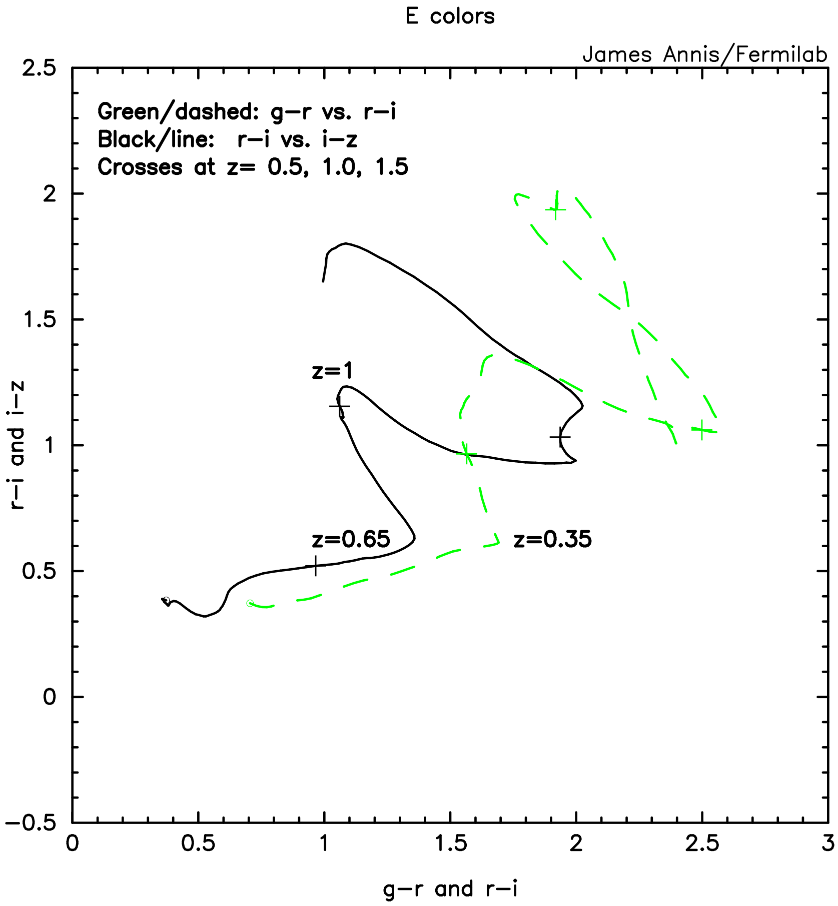

Fig. 1.4. Colors of $0.5L^{\star}$ galaxies in 4 bandpasses. These are the colors of ellipticals from $z = 0$ to $z = 2$. Marked with redshift labels are the points where the 4000 A break leaves the bluer bandpass.

If we are hard pressed, we can consider dropping a bandpass.

1.2.4 Exposure times

A calculation of the exposure time to reach a given magnitude at a given S/N depends on the mirror area (10 sq-meters for the 4m), the throughput of the system, the read noise of the instrument, the pixel size, the sky background, and the area over which the object is spread.

We have used three different exposure calculators: the web-based calculator for Megaprime, the web-based calculator for the CFHT 12k, and one that one of us (JTA) constructed to predict SDSS magnitudes.

Flowdown Requirements

1.2.4.1 J. Mohr

Using the CFHT exposure time calculator, I calculated exposure times for 10 sigma photometry of point sources with 1.1 arcsec seeing. I'm assuming this is crudely appropriate for distant, faint galaxies near our detection threshold.

Exposure times

Filter	g	r	i	z
mag(AB)	25.0	24.25	23.7	23.0
Dark	890	636	892	903*
Grey	2156	1012	892	903*
Bright	3992	1897	892	903*

* I've assumed that we have 1.5 times the QE in z band that MegaCam has.

First, note that there's no gain in doing i and z in dark time. So imagine the survey using dark time for g/r and bright time for i/z. We essentially need half our time to be dark and half bright, which means we want our observing to be spread equally between bright and dark time.

Assume that each sky pixel is built up from 5 sky different exposures in each band. Then each (4-bandpass) pixel requires 20 detector reads. Assume detector reads are 20s, and this corresponds to 400s for readout. Assume overhead for guide start acquisition and slewing for a total of 20% overhead on the exposure time listed above. This brings us to 4000s for the total time to acquire the survey data.

1.2.4.2 J. Annis

First, we assume that the system throughput in z is 40%, rather than the 10% of the SDSS. We assume the readnoise is $10e^{-}$, and the pixel size is 0.25"/pixel. The sky background is that from APO, the 25% quartile (bright) of all the frames of all the runs taken in the SDSS:

Sky brightness

filter	g	r	i	z
mag/sq-arcsec	21.7	20.7	20.0	18.7

though we note that a half magnitude increase in the sky brightness results in a quarter magnitude decrease in the limiting magnitude. The solar cycle causes sky brightness variations on order of 0.5 magnitude. The next solar max is roughly 2012. The sky brightness above are from the SDSS data, taken in the years right across the last solar maximum.

The Blanco has a 10.0 sq-meter collecting area. I assume a factor of 0.9 less transmission across all filters relative to the SDSS as there will be 2 more optical elements.

The area over which an object is spread is more tricky. A star is best case, and a very spread out object is worst case. Further, the Megaprime calculator assumes, for galaxies, that the intent is to measure 95% of the objects flux which takes a large aperture (think Petrosian magnitudes). For colors, one wishes a more compact apodized aperture; PHOTO uses a (seeing-convolved) deVaucouleurs profile to measure the color of faint ellipticals. This is effectively a factor of 1.7 larger than a PSF (determined empirically). We assume the 4m seeing is 1.0", and use a conservative aperture of 1.7" diameter to measure the flux.

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Exposure Times for 10σ

filter	g	r	i	z
mag (10σ)	23.1	23.7	24.3	23.2
exposure	40	230	1700	700

Magnitude Limits for 900s Exposures

filter	g	r	i	z
exposure	900	900	900	900
mag (10σ)	25.0	24.5	24.0	23.3

where I've converted to 10σ from 13 by adding 0.3 magnitudes, and I neglected multiple exposure read noise terms. The first set of exposure times are those required to reach the minimum limiting magnitudes, the second are what constant exposure times of 900 seconds provides. The only filter that could use deeper exposures than 900 seconds is the i band, where 1700 seconds is necessary. Thus:

filter:	g, r, i, z
exposure time:	900, 900, 1700, 900
total exposure :	4400 seconds per field.
overhead:	30 seconds pointing, 20 images: 600 seconds.
standards:	600 seconds/field
total:	5600 seconds/field

1.2.4.3 H. Lin

I'm using the CFH12K version of the DIET exposure time calculator (see the tables at http://www.cfht.hawaii.edu/Instruments/Imaging/CFH12K/DIET/CFH12K-DIET.html#P3 in particular the one labeled "Galaxies in dark time"), which differs from the MegaCam version of DIET in that it uses a smaller aperture for galaxies. As Jim and I discussed, this smaller, higher S/N aperture is more appropriate for getting good color measurements for small, faint galaxies.

Aperture Sizes for Galaxy Colors

DIET version	Target	x seeing	comment
CFH12K	point source	1.45	
CFH12K	galaxy	1.67	more appropriate for colors
Megaprime	galaxy	2.8	aimed at total magnitude

Using one field in my CNOC2/CFH12K data where I have two 15 min exposures in each of the VRI filters (and seeing 0.6-0.8 arcsec), I confirmed the CFH12K/DIET numbers by checking the SExtractor (aperture) magnitude scatter for the same objects between the different exposures (I haven't excluded the stars yet, but they will be largely outnumbered by galaxies at these faint magnitudes). One caveat, though, is that the 10σ limit from CFH12K/DIET is right about where the number counts in the data start to bend and turn over, i.e. it's close to the completeness limit. I'd feel more comfortable if in one filter, say I band, we would go a little bit deeper so that we can more safely construct a flux-limited sample to a given depth, in addition to being able to measure good colors to that same depth.

In the case of i, I have checked that the MegaCam and CFH12K DIET numbers are in reasonable agreement, after accounting for all the differences in seeing, bandpass, etc.

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The I_{AB} limits are 23.7 and 24.1 for 15 and 30 min exposure times, interpolating from the CFH12K/DIET tables, for 10σ galaxies, dark time, 0.9 arcsec seeing, airmass = 1.0, plus the conversion $I_{AB} = I_c + 0.432$ (for Cousins Ic; from Fukugita et al. 1995, PASP, 107, 945), plus another 0.08 mag deeper by accounting for the larger CTIO vs. CFHT mirror aperture.

The conversion to SDSS i band depends on redshift and galaxy type. From Fukugita et al., I get for an elliptical:

$$z = 0.0 \quad i = Ic + 0.53 \quad = I_A B + 0.10 \tag{1.1}$$

$$z = 0.8 \quad i = Ic + 0.74 \quad = I_A B + 0.31 \tag{1.2}$$

So at z=0.8, we would get to 10σ i = 24.0 and 24.4 (15 and 30 min) for an elliptical.

1.2.5 Time Available for the Survey

NOAO has guided us to assume 30% of the available time over 5 years.

1.2.5.1 J. Annis

Assume we get 4 months a year for 5 years. Assume we use all of it.

Assume we can can use i and z band in moon time. The indication from figure 1.5 is that the z band is insensitive to moonlight, and that the i band is insensitive if one maintains a 60° separation between the target and the moon.

Using http://www.ctio.noao.edu/facil/s7/sec7.html:

	photometric hours/day	cirrussy hours/day	time w/airmass ≤ 1.5
October	5.5	1.7	0.66
November	6.0	1.2	1.0
December	6.6	0.7	1.0
January	6.7	1.0	0.66

This gives us **630 hours per year of photometric time**, and over the 5 year survey 3150 hours.

1.2.5.2 W. Wester

An estimate of the dark time available between Aug 15 and Dec 15 and where RA $21^h - 3^h$ is less then zenith angle 45° gives:

Year	2007	2008	2009	2010	2011
hours	510	510	610	470	480

For a median value of **500 hrs/year of useful dark time**. This assumes only dark time is useful, but that we get -all- the dark time.

1.2.5.3 J. Frieman

There are useful pages at the CTIO web site. The seeing statistics listed under "FWHM seeing comparison" at the seeing stats page is interesting.

Seeing stats	http://www.ctio.noao.edu/telescopes/opteng/optics.html
Cloud cover	http://www.ctio.noao.edu/site/phot/sky_conditions.html,
Night Summary table	http://www.ctio.noao.edu/facil/s7/sec7.html.

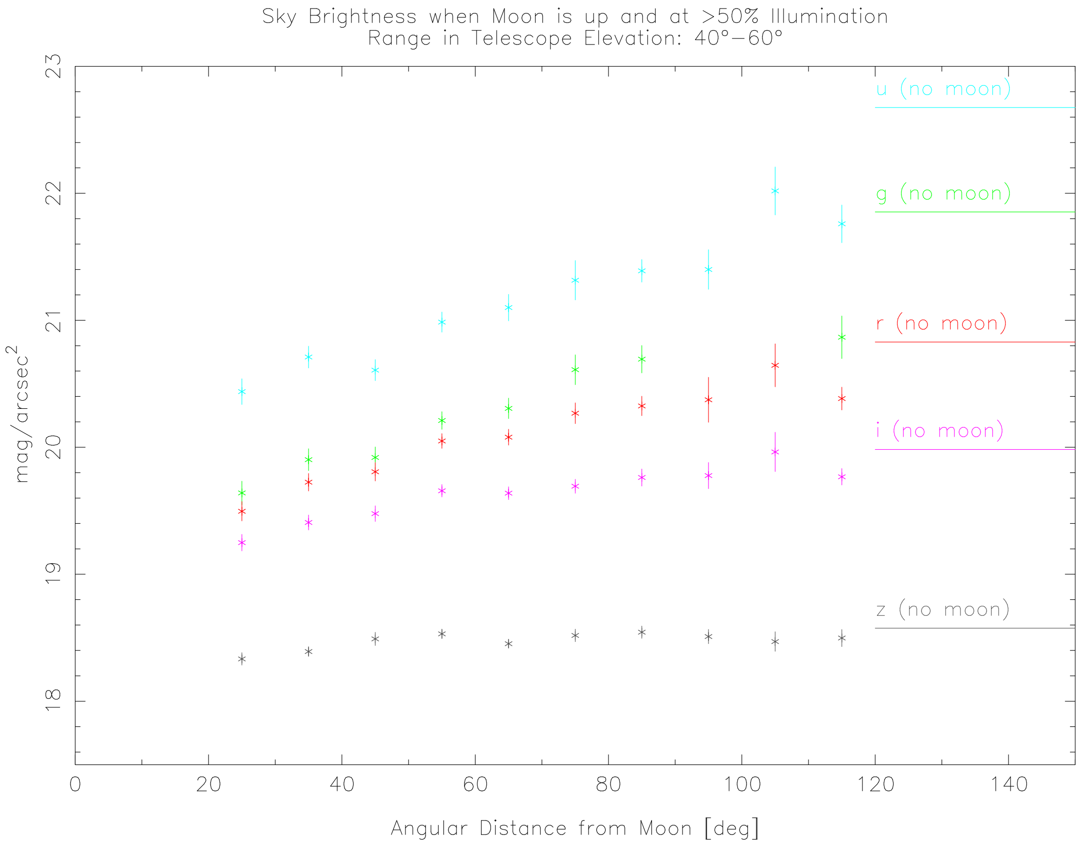

Fig. 1.5. The brightness of the sky during full moon, from SDSS PT data courtesy of Douglas Tucker.

Assume 5 months observing and 2 weeks a month, or 70 nights of dark/gray time. If 60% of that time is photometric then we get **250 hours/year of photometric dark time**. This assumes only dark time is useful. Note also that this uses up 2.5 months of the 4 allocated to us under the 30% rule.

Seeing

Month	Aug	Sept	Oct	Nov	Dec	Jan
median seeing	0.9"	0.9"	0.85"	0.65"	0.65"	0.60"

Median seeing taken from the “FWHM seeing comparison” page. Note that this is the site seeing, not the seeing at the 4m, which is for 10 minute exposures and by all accounts, more like 0.9” in the summer (i.e., January).

1.2.5.4 J. Mohr

Using http://www.ctio.noao.edu/facil/s7/sec7.html:

Useful nights

Month	Aug	Sept	Oct	Nov	Dec	Jan
hours/night	11.8	10.9	9.9	8.9	8.2	
photometric hrs/night	5.7	5.7	5.5	6.0	6.6	
useful hrs/night	8.0	7.6	7.2	7.2	7.3	

Then there are 1491 hours/year available, 1119 (75%) are useful, and 885 (59%) are photometric. We can expect about 70% of this time allocated to us for observing, for a final total of **637 hrs/year of photometric time.** This assumes we can use bright time.

1.2.5.5 Summary

If we can work into bright time, we can expect on order of **600 hrs/year of photometric time.**

1.2.6 Size of the Camera

The camera size then falls out.

To do a 5000 sq-degree survey in 3000 hours implies 1.67 sq-degrees/hr. The exposures take 5600 seconds (1.56 hrs) per field. Then

FOV = 1.67 sq-degree/hr * 1.56 hrs/field = 2.6 sq-degrees/field

If we have overestimate the times required, say 4000 seconds per field, than FOV = 1.8 sq-degrees/field. If we have underestimated, say 6000 seconds per field, then FOV=2.8 sq-degrees.

Note that a corrector with a 2.1° diameter field of view has 3.5 sq-degrees available in the circular area. But the largest useful pattern in that circular area is a hexagon, which if inscribed in that circle has an area of 2.9 sq-degrees. Further, the dead area between CCDs tends to be about 10%, leading to an active area of 2.6 sq-degrees.

1.2.7 Read Noise Requirements

1.2.7.1 J. Mohr

Minimum exposure time where sky noise is ten times read noise; read noise assumed to be 10 e- and pixel size is 0.25 arcsec; would be 4 times shorter with 5e- read noise.

Min Exposure to sky noise 10x readnoise

Filter	g	r	i	z
time (s)	220	200	100	70

1.2.7.2 J. Annis

The sky noise and the read noise add in quadrature. If the readnoise is taken to be $10e^{-}$, then

Read noise as % of sky noise

read noise	sky noise	total noise	% increase over sky noise
10	$1 \cdot \sigma_{rn}$	14	40%
10	$2 \cdot \sigma_{rn}$	22	10%
10	$3 \cdot \sigma_{rn}$	32	5%
10	$4 \cdot \sigma_{rn}$	41	3%

It would seem that as long as the readnoise is a factor of 1/2 or smaller than then the sky noise, we are fine.

1.2.8 Number of Exposures and Readout Times

Differential refraction across the $\geq 2°$ field of view contributes significantly at longer exposures and higher airmasses. The calculation I did was at 2 airmasses, where at 4 minute exposures the effect was 0.2”, whereas at 10 minutes it was a significant fraction of an arcsecond. We wish good PSF sizes for S/N reasons, so we either need an atmospheric dispersion corrector or limit exposures to 3 minutes. The latter is cheaper.

Multiple exposures are needed in any case for cosmic rays, gaps between devices, and photometric stability. As the time available calculation assumed no overhead, the read out time of the camera must be «180 sec, say $\leq$ 10 second readout time

1.2.9 Flowdown Requirements: Pixel Scale

Given that one must sample the PSF by at least 2 and preferably 3 pixels to do accurate photometry, that the site/dome delivers 0.75” images, and the prime focus image scale is 1 meter/5 degrees, the size of the pixels in the sensor must be $\leq$ 15 micron pixels.

If we have 0.9" seeing and 15 micron pixels, this is 3.4 pixels across the FWHM, just fine. If we have 10.5 micron pixels (0.19"/pixel), there are 4.8 pixels across the FWHM something of overkill, but not by a factor of 2.