DESI Science Requirements Document

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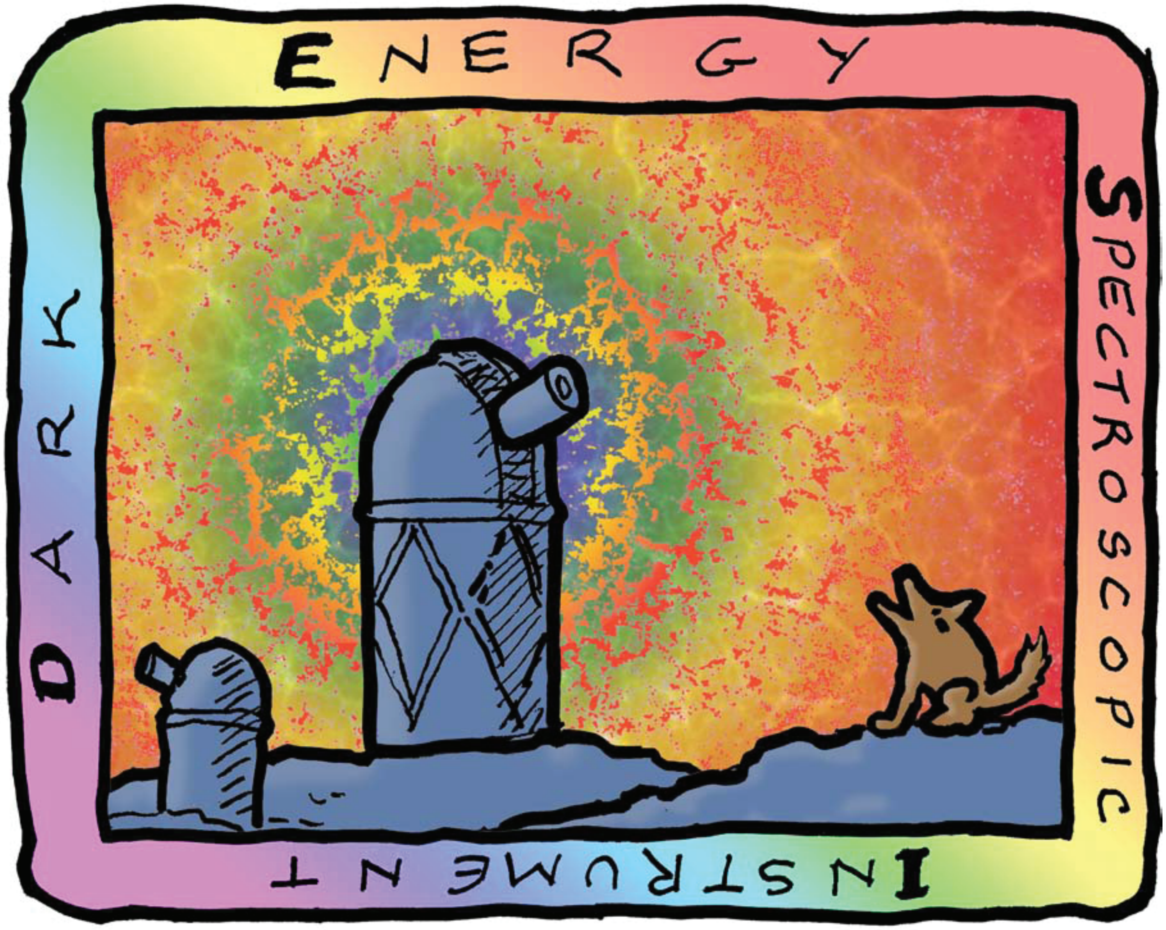

DESI Science Requirements Document

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I Introduction

The discovery that the expansion of the Universe is accelerating poses one of the biggest mysteries in science. This phenomenon could arise from a smoothly distributed form of dark energy, e.g., the cosmological constant, or it may signal the breakdown of General Relativity on cosmological scales. Either would be important. The primary scientific purpose of the Dark Energy Spectroscopic Instrument (DESI) is to probe the origin of cosmic acceleration by employing the baryon acoustic oscillation (BAO) technique as a "standard ruler" to measure the expansion history of the Universe with improved precision, extending the measurement back to redshifts of $z \sim 3.7$. To achieve this purpose, the DESI collaboration will use a new wide-field, multi-fiber spectroscopic instrument (DESI) on the Mayall 4-meter telescope at KPNO to carry out a massive, wide-area spectroscopic survey of order 20 million galaxies and 2 million QSOs in the North and South Galactic caps.

For the purposes of this document, we will assume that cosmic acceleration can be attributed to dark energy characterized by its effective equation of state parameter, $w(z)$, and its cosmic density, ρ_{DE}. DESI is designed to deliver "Stage IV" BAO precision on dark energy parameters, employing the definitions used by the Dark Energy Task Force (DETF) in their 2006 report [1].

I.1 Core Mission: Baryon Acoustic Oscillations (BAO)

Conceptually, the BAO signal is a modulation of the galaxy density and velocity field with a length scale $s \sim 100\ h^{-1}$ Mpc, where h is the local value of the Hubble constant H_0 in units of 100 km s^{-1}Mpc^{-1}. Due to the large scale of the BAO feature, BAO measurements are robust, and their accuracy can be reliably estimated using statistical errors due to the absence of significant systematic uncertainties on these scales. This feature distinguishes BAO measurements relative to other techniques considered by the DETF.

While the BAO signal is isotropic at any location, the quantities one measures are different in the radial versus the tangential directions. Radially, one measures a redshift separation $\Delta z_{\mathrm{BAO}} \propto sH(z)$, while tangentially one measures an angle $\Delta\theta_{\mathrm{BAO}} \propto s/D_A(z)$, where $H(z)$ is the Hubble parameter and $D_A(z)$ is the angular diameter distance H and D_A are functions of redshift, z, and depend on the dark energy parameters. We also define an isotropic BAO distance scale $R(z)$ as a combination of $H(z)$ and $D_A(z)$, similar to the parameter $D_V(z)$ defined in [3].

The DESI survey will be conducted with a new multi-object spectrograph and corrector installed on the Mayall telescope. The performance of the instrument is defined in the Conceptual Design Report (CDR; DocDB-315). The survey will span up to five years of observations, with the expected weather conditions (usable weather, seeing, and sky brightness) as defined in the DESI Site Alternatives Study (DocDB-311 v1). The redshift distributions for the galaxies and quasars are described in the CDR Sec. 3. The projected precision in distance errors and cosmological parameters is listed for a minimum 9000 and baseline 14,000 square degree survey in Tables 1 and 2. These calculations were performed as described in [4].

While this survey goal is achievable, it has little or no margin for reduced performance, unusually poor weather or other unanticipated problems. For the purposes of setting scien-

Table 1: DESI $z < 1.9$ galaxy and quasar clustering survey. The minimum survey to meet requirements is 9000 deg^2, and the baseline survey covers 14,000 deg^2. $\sigma_{f\sigma_{k_{\max}}}$ is the projected error (%) on the redshift-space distortion measurement of $f\sigma_8$ using $k < k_{\max}$ $h\mathrm{Mpc}^{-1}$.

	9k					14k				
z	$\frac{\sigma_{R/s}}{R/s}$	$\frac{\sigma_{D_A/s}}{D_A/s}$	$\frac{\sigma_{Hs}}{Hs}$	$\frac{\sigma_{f\sigma_{0.1}}}{f\sigma_{0.1}}$	$\frac{\sigma_{f\sigma_{0.2}}}{f\sigma_{0.2}}$	$\frac{\sigma_{R/s}}{R/s}$	$\frac{\sigma_{D_A/s}}{D_A/s}$	$\frac{\sigma_{Hs}}{Hs}$	$\frac{\sigma_{f\sigma_{0.1}}}{f\sigma_{0.1}}$	$\frac{\sigma_{f\sigma_{0.2}}}{f\sigma_{0.2}}$
0.65	0.70	1.01	1.86	4.08	1.94	0.56	0.81	1.49	3.27	1.55
0.75	0.59	0.85	1.57	2.60	1.25	0.47	0.68	1.26	2.08	1.00
0.85	0.58	0.85	1.51	2.62	1.25	0.47	0.68	1.21	2.10	1.00
0.95	0.60	0.89	1.50	2.59	1.22	0.48	0.71	1.20	2.07	0.98
1.05	0.70	1.08	1.67	2.76	1.36	0.56	0.87	1.33	2.21	1.09
1.15	0.72	1.12	1.68	2.77	1.39	0.58	0.90	1.35	2.22	1.11
1.25	0.73	1.14	1.68	2.77	1.40	0.58	0.92	1.35	2.22	1.12
1.35	1.07	1.72	2.35	3.51	2.05	0.85	1.38	1.89	2.81	1.64
1.45	1.12	1.81	2.46	3.68	2.20	0.90	1.45	1.97	2.95	1.76
1.55	1.30	2.11	2.83	4.18	2.62	1.04	1.69	2.27	3.35	2.10
1.65	1.84	2.98	4.00	5.73	3.92	1.47	2.39	3.21	4.60	3.14
1.75	2.68	4.30	5.89	8.84	6.50	2.15	3.45	4.72	7.09	5.21
1.85	2.71	4.36	5.96	9.16	6.74	2.17	3.49	4.78	7.34	5.40

Table 2: DESI $z > 1.9$ Ly-α forest and quasar clustering survey. BAO distance measurement errors are shown for the minimum 9000 deg^2 survey and the baseline 14,000 deg^2 survey. The number densities are the same for both surveys. Note that the lowest redshift quasars here would be used for clustering but not Ly-α forest absorption. Parameter errors in percent.

		9k			14k		
z	$\frac{dN_{QSO}}{dz\ \mathrm{ddeg}^2}$	$\sigma_{\ln R/s}$	$\sigma_{\ln D_A/s}$	$\sigma_{\ln Hs}$	$\sigma_{\ln R/s}$	$\sigma_{\ln D_A/s}$	$\sigma_{\ln Hs}$
1.96	115	1.41	2.57	2.77	1.13	2.06	2.22
2.12	79	1.27	2.42	2.48	1.02	1.94	1.99
2.28	53	1.40	2.78	2.68	1.12	2.23	2.15
2.43	43	1.52	3.13	2.87	1.22	2.51	2.30
2.59	37	1.69	3.63	3.13	1.36	2.91	2.51
2.75	31	1.93	4.30	3.49	1.55	3.45	2.80
2.91	26	2.28	5.31	4.00	1.83	4.26	3.21
3.07	21	2.71	6.63	4.64	2.17	5.32	3.72
3.23	16	3.44	8.88	5.71	2.76	7.12	4.58
3.39	13	4.83	13.08	7.75	3.87	10.49	6.21
3.55	9	7.22	20.04	11.22	5.79	16.07	8.99

tific requirements, the survey size is scoped to provide high-level overall project contingency. The minimum required survey size is 9000 $\deg^2$, and the baseline survey with contingency is set at 14,000 $\deg^2$. The minimum survey would measure $R(z)$ to aggregate precision 0.21% over the redshift range $0 < z < 3.7$, meeting the definition established by the DETF for a Stage IV BAO survey. The baseline 14,000 $\deg^2$ survey surpasses this minimum requirement by reaching a precision of 0.17%.

I.2 Cosmology Studies Beyond BAO

The scientific returns from the survey are not limited to BAO alone. The DESI redshift survey will enable studies of alternatives to dark energy and other physics questions. These studies do not drive the DESI requirements, but this document outlines the impact of the requirements on these studies.

DESI will test General Relativity using the technique of redshift space distortions (RSD). As part of the survey goals, DESI will measure the factor $f(z)\sigma_8(z)$, which describes the growth of structure, to the few percent level over the range $0.5 < z < 1.6$. This sensitivity is sufficient to discriminate between a cosmological constant and models of modified gravity and represents a very significant improvement over current constraints: a factor of $\sim 4 - 9$ in raw sensitivity (i.e., the error on measuring the amplitude for fixed redshift dependence of $f\sigma_8$) as well as more comprehensive redshift coverage.

DESI will test inflation using the combined galaxy and quasar power spectrum. DESI has the statistical power to improve the Planck measurement of running of the spectral index, α_s, to a precision of 0.004 with galaxy broad-band, and potentially to a precision of 0.002 when including Ly-α broad-band. This precision approaches an interesting regime for detecting values of α_s predicted by inflation. A detection of this key prediction of inflation would represent a major scientific discovery.

DESI will tightly constrain the sum of neutrino masses. Using the combined power of galaxy and Ly-α forest BAO and power spectrum measurements, DESI is predicted to have 1σ sensitivity of ~ 0.02 eV on the sum of neutrino masses. The minimum possible neutrino mass of 0.057 eV would be detected with a confidence of 2.4σ.

I.3 Figure of Merit

The DETF report [1] defined a Figure of Merit (FoM) to describe the reach of dark energy experiments and methods. Parameterizing the evolution of the dark energy equation of state by $w(a) = w_0 + w_a(1 - a)$, where $a(t) = 1/(1 + z(t))$ is the cosmic scale factor, the DETF FoM is a measure of the reciprocal of the area of the error ellipse in the $w_0 - w_a$ plane. Defining a pivot expansion factor a_p at which the uncertainty in $w_p \equiv w(a_p)$ is minimized for a given method (and, equivalently, the errors on w_p and w_a are independent, where the formula for $w(a)$ is now $w(a) = w_p + w_a(a_p - a)$) the DETF FoM is $1/[\sigma(w_p)\sigma(w_a)]$. While the DETF FoM is not a unique way to specify dark energy constraints, it provides a useful metric by which to compare the scientific reach of different experiments.

The DETF defines stages for experiments that represent major advances in dark energy constraints and FoM. Stage II experiments were those in progress at the time of the report. Stage III experiments are those improving upon the Stage II FoM by at least a factor of 3, and include the BOSS BAO experiment (now completed) and the Dark Energy Survey experiment (in progress). DESI will improve upon the Stage III FoM by a factor of 3, consistent with expectations for a Stage IV experiment. The DESI Key Performance Parameter Survey (over 9000 square degrees) will achieve this FoM using the BAO technique alone. The baseline 14,000 square degree survey described in the CDR would exceed this FoM with a significant margin. (Table 3) gives the DETF FoM for DESI and a comparison to Stage III BAO, represented by BOSS. Planck priors are included in all FoMs. DESI's requirement survey would improve on BOSS by a factor ~ 3 in the DETF FoM using the BAO technique alone, while the baseline survey would achieve a factor ~ 4 improvement. Much larger FoMs can be achieved using a full broadband power analysis. Because the exact values of the FoM are dependent upon detailed choices of priors and performance of ongoing experiments, DESI does not define its Level 1 requirement as a FoM value.

Table 3: DETF Figures of Merit for mininum requirements 9000 deg^2 and baseline 14000 deg^2 surveys.

Technique	BOSS	DESI	
		9k	14k
Galaxy + Ly-α BAO	37	114	143
+DESI galaxy broad-band power to $k = 0.1$ hMpc^{-1}		229	303
+DESI galaxy broad-band power to $k = 0.2$ hMpc^{-1}		525	687

Level 1 Scientific Requirements

In this section we identify the high level science requirements for the DESI BAO survey. The requirements come from the minimal required survey performance described in Tables 1 and 2. The top-level science requirements (Level 1) motivate the survey dataset (Level 2) and the experimental implementation (Level 3). We project the performance of both the minimum survey to reach requirements (over 9000 deg^2), and the baseline survey of 14,000 deg^2. The choice of survey area does not impact the Level 2 or Level 3 requirements.

L1.1 *The DESI survey shall cover at least 9000 deg^2. The baseline survey with margin covers 14,000 deg^2.*

Motivation: Area can generally be traded against number density, with equal BAO distance performance, according to the approximate formula:

$$\text{rms BAO distance errors} \propto \frac{1 + \frac{1}{\bar{n}P}}{\sqrt{\text{Area}}} \qquad (1)$$

(this formula strictly speaking only applies to power spectrum errors at the wavevector $\mathbf{k}$ where $P(k, \mu)$ is evaluated, but can approximate the scaling of BAO errors if a typical relevant $\mathbf{k}$ is used, like $k = 0.2$ hMpc^{-1}, $\mu = 0$, or $k = 0.14$ hMpc^{-1}, $\mu = 0.6$. At a fixed number of targets this formula has a minimum at $\bar{n}P = 1$, the origin of the idea that $\bar{n}P = 1$ is optimal. The DESI survey is in the $\bar{n}P > 1$ regime of diminishing returns over much of the redshift range, suggesting that more area should be sought out, or at least the available area maximized. More sophisticated optimization studies agree. Large numbers of new targets will be required to compensate any reduction in area. The other Level 1 goals similarly favor maximizing area.

The maximum area that is practical to achieve from the latitude of KPNO is 14,000 deg^2 due to Galactic plane avoidance and increasing atmospheric extinction at low declinations.

L1.2 *The DESI galaxy and low-z quasar survey will measure the isotropic cosmic distance scale* $R(z)$ *from the BAO method to 0.28% precision aggregated over the redshift bin* $0.0 < z < 1.1$ *and to 0.39% precision in the redshift bin* $1.1 < z < 1.9$*. For the baseline survey with margin, the distance scales will be measured to 0.22% and 0.31% precision.*

Motivation: Cosmic variance limits the ultimate BAO precision of any conceivable survey no matter how extensive (or expensive). The full-sky, zero shot noise cosmic variance limit on $R(z)$ assuming 50% reconstruction is 0.10% in each of two redshift bins, 0.6-1.1 and 1.1-1.4. The baseline 14,000 square degree survey has aggregate precision of 0.22% and 0.37% in these bins, within a factor of 2-4 of the cosmic variance limit. The difference between the DESI precision and the ultimate experiment is primarily due to the fact that only 1/3 of the full sky can be observed and to the presence of shot noise in the data due to a finite number of objects. The DESI minimum-requirement survey has errors a factor $(14/9)^{1/2}$ larger, 0.28% and 0.46% in the redshift ranges 0.6-1.1 and 1.1-1.4 respectively, within a factor 3-5 of the cosmic variance limit.

Aggregate measures of distance precision are reported at redshifts $z < 1.1$, where DESI overlaps other probes such as Type Ia supernovae, and at redshifts $1.1 < z < 1.9$. The DESI requirements can be met with different choices of the detailed redshift distribution.

Explanation: These requirements are generated using a Fisher matrix calculation for a DESI survey of 9,000 square degrees, as shown in Tables 1 and 2. We aggregate measurements over the wide redshift bins by taking the inverse square root of the sum of inverse variances in individual narrower bins. This calculation assumes that the reconstruction technique is used to reduce the non-linear effects by 50% [5], similar to what has already been achieved in BOSS.

This requirement is based on the BAO method using LRGs, ELGs and QSOs as tracers of the underlying matter distribution; contributions from the quasar Ly-α forest method are not included. Here, "the BAO method" refers to analyses in which one marginalizes against broadband nuisance terms so as to focus strictly on the acoustic peak (see [2] for an example). Higher precision may well be obtained with analyses using more of the broadband information.

L1.3 *DESI will measure the Hubble parameter at* $1.9 < z < 3.7$ *from the BAO method to 1.05%; 0.84% for the larger baseline survey.*

Motivation: A 1% measurement of the Hubble parameter corresponds to a 2% measurement of the cosmological density. At a redshift of 2.5, a cosmological constant would comprise 5% of the density of the Universe. The uncertainty on the matter density (comprising the remaining 95% of the energy density) is well below 2%. Hence, a 1% measurement of the Hubble parameter produces a 2.5σ detection of the cosmological constant's effects at these redshifts, and the baseline survey would deliver a 3σ detection. Models with $w > -1$ have more dark energy at high redshifts and hence would be easier to detect. Models with $w \ll -1$ would be disfavored by any detection of dark energy at $z > 2$.

The angular diameter distance measured at these redshifts places important constraints on the spatial curvature of the Universe and strong dark energy at $3 < z < 1000$. We do not place a separate requirement on D_A as the Hubble parameter requirement should be sufficient to ensure D_A performance and because $H(z)$ is more directly tied to a test of dark energy.

Explanation: DESI will measure the Hubble parameter at high redshift using Ly-α forest, supported by cross-correlations between the forest and other tracers (e.g., quasars themselves). These numbers are Fisher matrix estimates as shown in Table 2, computed as described in [4]. The BOSS experiment demonstrated the feasibility of this technique and our projections are supported by the BOSS results.

L1.4 *The galaxy survey at $z < 1.5$ shall be capable of separately determining $D_A(z)$ and $H(z)$ from the BAO without instrumental and survey uncertainties degrading the performance available from the sky. In particular, the systematic errors from the instrument and observational methods must not exceed 0.16% for D_A and 0.26% for H.*

Motivation: The exact astrophysical performance available on $H(z)$ is not as firmly known as $R(z)$. Therefore, we opt to set the Level 1 quantitative requirement on $R(z)$ and phrase the $H(z)$ requirement as a limit on instrumental systematics.

The forecasted statistical errors on $H(z)$ in Table 1, scaled to the minimum-requirement 9000 deg^2 survey, are an aggregate of 0.58% for the redshift range 0.0 to 1.5. Adding 0.26% in quadrature would degrade the total error by 10%. Similarly, the aggregate errors on D_A in this redshift range are 0.35%. Adding 0.16% in quadrature again would be a 10% increase in total error.

We apply this requirement to $z < 1.5$ where LRGs and ELGs are the dominant tracer and redshift measurement errors are small and well-understdood.

Level 2 Survey Data Set Requirements

L2.1 Overview

To satisfy the Level 1 science requirements, DESI will conduct a spectroscopic survey of luminous red galaxies (LRGs), emission line galaxies (ELGs), and quasars (QSOs) that provide continuous coverage in redshift out to $z \sim 3.7$.

The survey parameters for the DESI minimum-requirements and baseline surveys are given in Table 4. The survey multiplexes four main target classes: LRGs, ELGs, tracer QSOs (at $z < 2.1$), and high-redshift QSOs (at $z > 2.1$) suitable for measuring the Lyman-alpha forest. Operationally all these target classes will be observed simultaneously, and total exposure times for each target are restricted to multiples of the nominal exposures. Each target is observed with sufficient exposure to achieve the redshift completeness for that class, or to achieve the required S/N in the Lyman-alpha forest for the high-redshift QSOs.

Table 4: Survey parameters for the minimum-requirement 9000 deg^2 and the baseline 14000 deg^2 surveys.

			Number of successful objects	
Object Type	Redshift Range	N/deg^2	9,000 deg^2	14,000 deg^2
LRGs	0.4–1.0	300	2.7×10^6	4.2×10^6
ELGs	0.6–1.6	1280	11.5×10^6	17.9×10^6
tracer QSOs	<2.1	120	1.1×10^6	1.7×10^6
Ly-α QSOs	>2.1	50	0.45×10^6	0.7×10^6

L2.2 Luminous Red Galaxies

Luminous Red Galaxies (LRGs) are the reddest, most luminous galaxies in the Universe at redshifts $z < 1$. These galaxies can be efficiently identified in imaging surveys in combination with the completed Wide-Field Infrared Survey Explorer (*WISE*) satellite data. The LRG redshift identification is dominated by the 400 nm break feature, which is measurable by the DESI spectrographs to $z = 1.4$.

L2.2.1 *The average density of successfully observed, galaxy clustering science-quality LRGs with redshift* $0.4 < z < 1.0$ *shall be at least 300 deg*$^{-2}$ *(including BOSS LRGs over the BOSS area).*

Motivation: Reducing shot noise sufficiently to meet BAO distance error requirements at $z < 1.1$, L1.2 .

Explanation: LRGs are abundant at $z < 1$ and have a high bias relative to the underlying dark matter, making them an ideal target class to fulfill the $z < 1.1$ BAO distance requirement of L1.2. Their power level is $P_{\rm LRG}(k = 0.14\ h{\rm Mpc}^{-1}, \mu = 0.6) \simeq 14000\ h^{-3}{\rm Mpc}^3$ or $P_{\rm LRG}(k = 0.2\ h{\rm Mpc}^{-1}, \mu = 0) \simeq 6000\ h^{-3}{\rm Mpc}^3$. Shot noise is minimized with comoving number densities greater than $\sim 2 \times 10^{-4}(\ h^{-1}{\rm Mpc})^{-3}$, corresponding to a surface density of ~ 330 per square degree in the redshift interval $0 < z < 1.1$. DESI will target near this surface density so as not to be significantly limited by shot noise for the LRG target class.

Verification: BOSS and eBOSS data indicate that these LRG densities are achievable. This will be further verified with DESI pilot surveys and data during science verification.

L2.2.2 *The random error on individual LRG redshifts in a* $\sim$*Gaussian core shall be less than* $\sigma_z = 0.0005(1 + z)$ *(equivalent to 150 km/s rms).*

Motivation: Larger redshift errors damp the BAO feature in the radial direction, degrading the BAO distance errors relative to our $z < 1.1$ requirements and goals, L1.2, and especially the requirement to measure H separately from D_A, L1.4. They will similarly degrade the information content in the broadband power spectrum, and possibly lead to additional systematic errors if their distribution if not well-characterized .

Explanation: The BAO length scale is $100h^{-1}$ Mpc with a width ~ 8 $h\mathrm{Mpc}^{-1}$ (Silk damping scale [5]). A redshift error of 300 km/s is equivalent to convolving the BAO signal with a Gaussian whose 1σ width is ~ 3 $h\mathrm{Mpc}^{-1}$. At the densities we achieve in the LRG region, and for our assumed reconstruction, redshift errors $\sigma_z = 0.0005(1+z)$ degrade our rms R error by 0.6% and H error by 1.2%. A redshift error twice as large would degrade the R and H errors by 2.7% and 5.6%, respectively, but this is an unnecessary degradation as smaller redshift errors are easily achieved.
Verification: Science verificaion of LRGs with well-determined redshifts from deep plates from BOSS and eBOSS.

L2.2.3 *Systematic inaccuracy in the mean LRG redshift shall be less than* $\Delta\bar{z} = 0.0002(1+z)$ *(equivalent to 60 km/s).*

Motivation: A systematic offset in all redshifts implies a misinterpretation of the redshift at which the BAO distance is measured, effectively adding to the error on the BAO measurement at $z < 1.1$ (L1.2). Achieving this accuracy will be sufficient to eliminate this source of error.
Explanation: At the typical LRG redshift $z \sim 0.75$, an offset $\delta z = 0.00035$ corresponds to a 0.037% distance error, which increases the D_A error by 0.4%. As systematic errors in LRG redshifts are easily controlled, this requirement is set to a level where it can be ignored in the BAO analyses.
Verification: Science verificaion of LRGs with well-determined redshifts from deep plates from BOSS and eBOSS.

L2.2.4 *LRG redshift catastrophic failures exceeding 1000 km/s shall be* $< 5\%$*.*

Motivation: L1.2 BAO distance error requirements and goals at $z < 1.1$.
Explanation: The BAO measurement is tolerant to either unmeasured redshifts or incorrect redshifts that are assigned redshifts with a random distribution, but less so to redshifts that are incorrectly assigned and systematic. For LRGs, the danger is identifying "close" features incorrectly, such as confusion between the CaH and CaK absorption lines that would shift some redshifts by ~ 40 h^{-1}Mpc. Such mis-identifications would shift the bias $\xi(r)$ and $P(k)$.
Verification: Observations of LRGs in fields where existing ground data have confirmed redshifts. A sample size of $\sim 10,000$ will be necessary to measure this to $\sim 1\%$ accuracy.

L2.2.5 *The LRG redshift completeness shall be >95% for each pointing averaged over all targets that receive fibers.*

Motivation: To ensure that non-uniformity of the sample is small enough to not introduce biases in the analysis. The requirement is necessary to avoid corrupting the BAO distance measurement at $z < 1.1$ (L1.2) .
Explanation: Missing redshifts comprise objects that are not LRGs or have spectra that cannot be measured (e.g., object too faint, fiber miscentering). This requirement is based on experience with BOSS.
Verification: Inspection of data obtained during science verification.

L2.3 Emission Line Galaxies

Emission Line Galaxies (ELGs) are star-forming galaxies with strong emission lines that make them suitable for the DESI redshift survey. ELG redshift is tagged by identifying the [OII] doublet for $0.5 < z < 1.6$.

L2.3.1 *The average density of successfully observed, galaxy clustering science-quality ELGs shall be at least 1280 deg^{-2} for* $0.6 < z < 1.6$.

Motivation: Reducing shot noise sufficiently to meet BAO distance error requirements and goals (L1.2) to achieve a high precision galaxy broadband power measurement.
Explanation: The ELG power level is $P_{\rm ELG}(k = 0.14\ h{\rm Mpc}^{-1}, \mu = 0.6) \simeq 3957\ h^{-3}{\rm Mpc}^3$ or $P_{\rm ELG}(k = 0.2\ h{\rm Mpc}^{-1}, \mu = 0) \simeq 1371\ h^{-3}{\rm Mpc}^3$. Shot noise is minimized with comoving number densities greater than $3 \times 10^{-4}(\ h^{-1}{\rm Mpc})^{-3}$, or a surface density greater than 400 per square degree in the redshift range $0.6 < z < 1.1$ and 600 per square degree in the redshift range $1.1 < z < 1.6$. Achieving $\bar{n}P \sim 1$ achieves a BAO measurement with twice the error compared to a higher-density survey with no shot noise.
Verification: DEEP2 data indicate that these ELG densities are achievable. This will be further verified with DESI pilot surveys and data during science verification.

L2.3.2 *The random error on individual ELG redshifts in a ∼Gaussian core shall be less than* $\sigma_z = 0.0005(1 + z)$ *(equivalent to 150 km/s rms).*

Motivation: Larger redshift errors damp the BAO feature in the radial direction, degrading the BAO distance errors relative to the requirements and goals in L1.2, and especially the requirement to measure H separately from D_A, L1.4. They will similarly degrade the information content in the broadband power spectrum, and possibly lead to additional systematic errors if their distribution is not well-characterized .
Explanation: See explanation for LRGs (L2.2.2).
Verification: Observation of ELGs with known redshifts.

L2.3.3 *Systematic inaccuracy in the mean ELG redshift shall be less than* $\Delta\bar{z} = 0.0002(1+z)$ *(equivalent to 60 km/s).*

Motivation: A systematic offset in all redshifts implies a misinterpretation of the redshift at which the BAO distance is measured, effectively adding to the error on the BAO measurement (L1.2). Achieving this accuracy will be sufficient to eliminate this source of error.
Explanation: In the higher z range dominated by ELGs, $z \sim 1.3$, an offset $\delta z = 0.00046$ corresponds to a 0.024% distance error, which increases our D_A error by only $\sim 0.09\%$. This requirement should also be sufficient for lower z ELGs, as we discussed for LRGs. This requirement should be easy to achieve, so we want to make sure virtually no error propagates from it.
Verification: Observation of ELGs with known redshifts.

L2.3.4 *ELG redshift catastrophic failures exceeding 1000 km/s shall be* $< 5\%$.

Motivation: L1.2 BAO distance error requirements and goals , and goal to achieve a high accuracy galaxy broadband power measurement.
Explanation: The BAO measurement is tolerant to either unmeasured redshifts or incorrect redshifts that are assigned redshifts with a random distribution, but less so to redshifts that are incorrectly assigned and systematic. For ELGs, the danger is mis-identification between the [OII], [OIII] and Hα emission lines. Because the redshift vs. angular-diameter relation is fairly flat at $z \sim 1$, these mis-identifications could shift the apparent position of the BAO feature.
Verification: Observations of ELGs in fields where existing ground data have confirmed redshifts. A sample size of $\sim 10,000$ will be necessary to measure this to $\sim 1\%$ accuracy.

L2.3.5 *The ELG redshift completeness shall be* $> 90\%$ *for each pointing averaged over all targets above the [OII] flux limit.*

Motivation: To ensure that nonuniformity of the sample is small enough to not introduce biases in the analysis. The requirement is necessary to avoid corrupting the BAO distance measurement (L1.2) .
Verification: Inspection of data obtained during science verification.

L2.4 Tracer QSOs

QSOs are excellent BAO targets at redshifts $1 < z < 2.1$ where their number density peaks, although at values less than that of ELGs. They can be selected from g, r, and i-band photometry with a high contamination rate ($\sim 50\%$) from stars. The addition of deep u-band data, multi-epoch photometry in any optical band, or existing *WISE* data reduces this contamination rate.

L2.4.1 *The average density of successfully observed, QSO clustering science-quality tracer QSOs shall be at least 120* $\deg^{-2}$ *for* $z < 2.1$.

Motivation: While there are not enough possible targets to make a large contribution, QSOs make a small but efficient contribution toward the $z > 0.9$ BAO distance requirement L1.2.
Explanation: Recent measurements of the QSO luminosity function indicate an average number density of 130 $\deg^{-2}$ to a magnitude $g < 23$ and in the redshift range $1 < z < 2.2$. We expect to be able to successfully target and measure redshifts for approximately 2/3 of them. As discussed under L2.3.1, any increase in number density of objects decreases our BAO distance errors.

L2.4.2 *The random error on individual tracer QSO redshifts in a ∼Gaussian core shall be less than* $\sigma_z = 0.0025(1+z)$ *(equivalent to 750 km/s rms).*

Motivation: Tracer quasars make a modest contribution to the BAO measurement (L1.2) once ELGs become sparse. An rms error 750 km/s does increase the error on a BAO

measurement dominated by quasars by 25%, so we would ideally do better, however, we do not currently believe we can do much better than this.
Explanation: 750 km/s as a reasonable expectation is motivated by extensive experience with BOSS.
Verification: Observation of QSOs with known redshifts.

L2.4.3 *Systematic inaccuracy in the mean tracer QSO redshift shall be less than* $\Delta\bar{z} = 0.0004(1+z)$ *(equivalent to 120 km/s).*

Motivation: A systematic offset in all redshifts implies a misinterpretation of the redshift at which the BAO distance is measured, effectively adding to the error on the BAO measurement (L1.2). Meeting this requirement will make this source of error negligible.
Explanation: Experience from BOSS shows us that this error is achievable, and it is comfortably good enough to propagate no error, as discussed for ELGs (L2.3.3).
Verification: Observation of QSOs with known redshifts.

L2.4.4 *Tracer QSO redshift catastrophic failures exceeding 1000 km/s shall be* $< 5\%$*.*

Explanation: See LRG explanation (L2.2.4).
Verification: Observations of QSOs in fields where existing ground data have confirmed redshifts.

L2.4.5 *The QSO redshift completeness shall be* $> 90\%$ *for each pointing averaged over all targets.*

Verification: Inspection of data obtained during science verification.

L2.5 Ly-α QSOs

Ly-α QSOs are those objects at $z > 2.2$ that represent the only opportunity for DESI to measure dark energy at these high redshifts. Unlike the previous QSO target class, they are are used to trace the matter density along their lines-of-sight. This is the one target class where uniformity of the targeting information or selection algorithms is not required. The selection methods are the same as those for the QSO Tracers. The absence of a uniformity requirement allows the use of any available imaging data, even when covering only partially the footprint.

L2.5.1 *The average density of successfully observed, Ly-α forest and QSO clustering science-quality QSOs at* $z > 2.1$ *and* $r < 23.5$ *shall be at least 50 per deg*^{2}*.*

Explanation: This class of objects were already targeted with BOSS at an average density of 17 per deg^2. Recent measurements of the QSO luminosity function indicate an average number density of 53 deg^{-2} to a magnitude $g < 23$ and for the redshift range $2.2 < z < 3.5$. The required density therefore corresponds to a minimum of 75% of the total existing population.
Verification: DESI pilot surveys and simulation of future imaging data show this density is achievable.

L2.5.2 *The tracer QSO redshift accuracy shall be* $\sigma_z = 0.0025(1 + z)$ *(equivalent to 750 km/s rms).*

Explanation: Ly-α forest QSOs will also be used as tracers, at least in cross-correlations, so they have similar needs to low z QSOs.
Verification: Observation of QSOs with known redshifts.

L2.5.3 *The Ly-*α *QSO redshift catastrophic failures shall be* $< 2\%$*.*

L2.5.4 *The Ly-*α *QSO S/N per Angstrom (observer frame) shall be greater than 1 in the Ly-*α *forest (98.5 – 120 nm in the QSO restframe, or 360 – 570 nm observer frame), for* $g = 23$ *quasars, and scale approximately with luminosity for brighter quasars. Degraded S/N is allowed below* $\sim 4000\text{Å}$*, e.g., corresponding roughly to a smooth reduction to* $S/N > 0.5$ *at 3770Å.*

Motivation: Noise power in the spectra contributes directly to the error in the three-dimensional Ly-α forest power, and thus the error on the BAO distance measurement (L1.3).
Explanation: This level of noise has been assumed in the projection of L1.3 $H(z)$ errors. It is not negligible, but also not dominant. The setting of this requirement should be viewed as an optimization decision – it is not a sharp threshold. This impacts exposure time.
Verification: Early test data.

L2.6 Spectrophotometric Calibration

L2.6.1 *The Ly-*α *QSO fractional flux calibration errors shall have power less than 1.2 km/s at* $k \sim 0.001$ *s/km.*

Motivation: The Ly-α forest BAO distance errors (L1.3) are sensitive to the total power on this scale. This requirement will guarantee that flux calibration errors do not add more than $\sim 5\%$ to the error contributed by the intrinsic absorption fluctuations.
Explanation: We specify the requirement on power on a certain scale, $P(k \sim 0.001\text{s/km}) <$ 1.2 km/s, to be clear that this is what is really relevant. With $\Delta v = c\Delta\lambda/\lambda$ note that $(\pi/0.001)$ km/s corresponds to $\sim$ 40Å, i.e., this power requirement corresponds to approximately 2% rms fluctuations over $\sim$ 40Å stretches, where it must be understood that fluctuations due to a much larger scale smooth trend do not need to be included here, e.g., one can imagine that the spectrum is smoothed on $\sim$ 400Å scales and fluctuations are measured relative to that.
Verification: Studies of early test data.

L2.7 Fiber Completeness

L2.7.1 *The fraction of targets that receive a fiber shall be at least 80%.*

Motivation: A high fiber assignment completeness allows both a target selection that does not extend fainter than the DESI spectroscopic limits, and limits the magnitude of incompleteness corrections to the BAO measurements.
Explanation: The limited patrol radius of each individual fiber and the clustering of galaxies and QSOs prevents the DESI instrument from observing 100% of all targets. A

target density that utilizes nearly 90% of the fibers for the primary science targets after 5 passes achieves a fiber assignment completeness of 80%. Larger utilizations of the fibers can be traded against larer fiber incompleteness, but at the expense of observing fainter objects. Prioritization of fiber assignment between target classes is possible.
Verification: Fiber assignment will be tested with mock galaxy catalogs and then the real target catalogs as they become available.

L2.8 Target selection

This section gives estimates of the efficiency of target selection for each type of object, total number density of targets, and limiting fluxes that might be expected. The number of successful redshifts is derived from the total number of target candidates by applying the following factors:

1. Target selection efficiency
2. Fiber assignment completeness
3. Redshift measurement completeness

L2.8.1 *The LRG target density shall be 350 per deg^2, with at least 300 per deg^2 successfully measured (§L2.2.1). With a fiber assignment efficiency of 99% for LRGs, this implies a combined target selection and redshift measurement efficiency of 87%. The magnitude limit for this sample is* $z_{AB} < 20.56$.

L2.8.2 *The ELG target density shall be 2400 per deg^2, with at least 1280 per deg^2 successfully measured (§L2.3.1). With a fiber assigment efficiency of 82% for ELGs, this implies a combined target selection and redshift measurement efficiency of 65%. The magnitude limit for this sample is* $r_{AB} = 23.4$.

L2.8.3 *The low-z tracer QSO target density shall be 170 per deg^2, with at least 120 per deg^2 successfully measured (§L2.4.1). With a fiber assignment efficiency of 99% for tracer QSOs, this implies a combined target selection and redshift measurement efficiency of 71%. The limiting magnitude shall be 23 in the g band.*

L2.8.4 *The Ly-α QSO target density shall be 90 per deg^2, with at least 50 per deg^2 successfully measured (§L2.5.1). With a fiber assignment efficiency of 99% for Ly-α QSOs, this implies a combined target selection and redshift measurement efficiency of 72%. The limiting magnitude shall be 23 in the g band.*

Justification: The target selection efficiencies are based on estimates derived from various pilot surveys using SDSS, WISE, PTF, BOSS, and other data sets. The total number of target candidates are derived by straightforward arithmetic. The limiting fluxes or magnitudes are derived from the pilot surveys, DEEP2, and other surveys.
Verification: Existing pilot surveys. The final results will be tested during science verification.

Level 3 Imposed and Derived Technical Requirements

L3.1 Implementation

L3.1.1 *The Spectral Range shall be 360–980 nm.*

Motivation: Meets the redshift range requirement L1.2 for identifying the signature of the four target categories as summarized in Table 4.
Explanation: The short wavelength cutoff at 360 nm is given by the desire to measure: (a) the Balmer break at 364.6 nm for low-redshift interloper galaxies that could contaminate the targets; (b) the 361.0 nm Cd arc lamp line for calibration; (c) the QSO Ly-α line at 121.6 nm redshifted to 377 nm at $z = 2.1$; and (d) the full forest between Ly-α and Ly-β (rest frame 102.6 nm) for $z > 2.5$.

The long wavelength cutoff is determined by the detection of the ELG [OII] doublet up to $z = 1.6$, corresponding to 970 nm. LRGs will have the 400 nm spectral break measured for $z < 1.4$ the Mg b 517.5 nm absorption feature measured for $z < 0.89$, and the Na D 589.3 nm absorption feature measured for $z < 0.66$.

Wavelength coverage as measured by arc lamps by the spectrographs in the lab before delivery.

L3.1.2 *Spectral Resolution shall be (a)* > 1500 *at wavelengths* $360 < \lambda < 555$ *nm, (b)* > 3000 *at wavelengths* $555 < \lambda < 656$ *nm, and (c)* > 4000 *at wavelengths* $656 < \lambda < 980$ *nm.*

Motivation: Supports redshift measurement accuracy and precision, and catastrophic redshift error requirements: for LRGs (L2.2.2, L2.2.3, and L2.2.4), ELGs (L2.3.2, L2.3.3 and L2.3.4), QSO tracers (L2.4.2 and L2.4.4), and Ly-α QSOs (L2.5.2 and L2.5.3). For an ELG [OII] system detected at 7σ, the doublet is fit with a $\Delta\chi^2$ of 9 relative to a best-fit singlet line, thereby achieving a secure identification of this doublet feature.
Explanation: ELG redshift measurement predominately determines the required spectral resolution. Spectral resolution is defined as $R = \lambda/\Delta\lambda$, where $\Delta\lambda$ is the FWHM of the delivered spot size on the spectrograph sensor in the dispersion direction. For lower-redshift ELGs at $z < 0.49$ (where the [OII] doublet is at $\lambda < 555$) lower resolution is acceptable because the strong Hα emission line is seen in the spectra. For ELGs at redshifts $0.49 < z < 0.76$, the resolution $R > 3000$ is required to identify the [OII] doublet as a bright line. For ELGs at redshifts $0.76 < z < 1.6$, the resolution $R > 4000$ is required to identify the [OII] emission as a doublet.
Verification: Instrumental resolution as measured by arc lamps by the spectrographs in the lab before delivery.

L3.1.3 *The median S/N= 7 flux limit will be 10., 9, 9, 8, and* 9×10^{-17} *erg/s/cm*^{2} *in redshift bins of 0.6-0.8, 0.8-1.0, 1.0-1.2, 1.2-1.4 and 1.4-1.6 for an [OII] doublet emission line in an ELG galaxy with an exponential half-light radius of 0.45 arcsec observed in 1.1 arcsec seeing with the sky spectrum under median, dark-sky, photometric conditions.*

Motivation: Achieves the ELG target density in L2.3.1. Meeting the ELG requirement will achieve the target density for LRGs (L2.2.1), QSO tracers (L2.4.1), and Ly-α QSOs (L2.5.1).
Explanation: The flux limit is a function of the instrument throughput, resolution and read noise as well as the environmental conditions such as seeing and sky spectrum. The DESI spectroscopic simulations (QuickSim) are used to predict these flux limits as a function of redshift for the [OII] emission lines of ELGs. The existence of features in the sky spectrum modulates this flux limit as the [OII] feature crosses features, and the requirement is written as the median of that limit in redshift bins of $\Delta z = 0.2$. Increases in exposure time can lineary offset decreases in throughput.
Verification: The instrumental inputs to QuickSim will be updated as the instrument is constructed, allowing verification of predicted flux limits with the delivery and test of each component's peformance. For on-sky performance, DEEP2 or eBOSS spectra with known emission line strengths near these flux limits will be measured during commissioning.

L3.1.4 *The fiber density shall be less than 700 per square degree.*

Motivation: Meets the combined target density requirements for ELGs (L2.3.1), LRGs (L2.2.1), QSO tracers (L2.4.1), and Ly-α QSOs (L2.5.1).
Explanation: Different classes of object require different exposure times, with the Ly-α forest QSOs requiring 4× longer exposure time compared to ELGs and LRGs require 1, 2, or 3 times the ELG exposure time. The average science target density is 3190 per deg^2 with five visits per field (Table 3.1 of the Conceptual Design Report). This requires no more than 638 fiber per square degree. Significantly larger fiber densities would result in low targeting completeness and fewer possible observations for the Ly-α forest QSOs and LRGs.
Verification: By construction.

L3.1.5 *The field of view shall be no less than 7.65 square degrees.*

Motivation: Meets the required number of spectra (Table 4) in the allotted survey time (L3.2.1).
Explanation: Three requirements combine to constrain the telescope field of view: (a) the complete sky survey area A_{survey}, (b) the minimum required time in any one field T_{tile}, and (c) the on-target survey duration T_{survey}. Specifically, the number of fields (or *tiles*) that fill the survey area is

$$N_{tiles} = \frac{A_{survey}}{A_{tile}} = \frac{T_{survey}}{T_{tile}} \tag{2}$$

This relationship makes it clear that when we impose a minimum T_{tile} we will then limit N_{tiles} thereby imposing a minimum A_{tile}. From this relationship we evaluate the required

Table 5: Required tile area in square degrees for two DESI survey size scenarios.

Asurvey	Years	Hours	Atile
9000	3.5	2589	7.37
14000	5.0	3883	7.65

tile area for the two scenarios defined in Level 1: the minimum mission comprising a 9000 square degree survey spanning 3.5 years, and a baseline survey of 14,000 square degrees spanning 5 years:

$$A_{tile} = F_{over} \times \frac{A_{survey} \times T_{tile}}{T_{survey}} \tag{3}$$

If tiling were perfect, with no edge losses or overlaps, then F_{over}=1 would be sufficient. However a circular focal plane does not perfectly tile the sky, and additional focal plane area will be required. In a hexagonal pattern, circles tile an infinite plane without gaps if $F_{over} = 1.21$ which we adopt here.

The issue that governs T_{tile} is the longest required exposure on any one target class. This will be the QSO targets, both for clustering and for the Ly-α forest determinations. From Level 2 requirements, the QSO:LRG:ELG exposure time ratios will be approximately 5:2:1, and from Conceptual Design Report (DocDB-315 v4 p.103) the basic unit exposure time will be 1200 seconds. Allowing five exposures per QSO with 120 sec for inter-exposure readout and reconfiguring of the non-QSO fibers, we adopt a nominal T_{tile}= 6600 sec = 1.83 hours.

The issues that govern the available on-target duration T_{survey} are the calendar-years allowed for the DESI on-mountain operations, and the factors that limit on-target time:

$$T_{survey} = (T_{years} - T_{startup}) \times N_{nightsperyear} \times N_{hourspernight} \times F_{weather} \times F_{seeing} \times F_{moon} \tag{4}$$

Here we adopt the following factors:

$T_{startup} = 0.5$ years, allows for 50% operational efficiency during the first year;
$N_{nightsperyear}$ = 365 - 45 = 320 accounting for monsoon season;
$N_{hourspernight} = 9.0$, astronomical night, averaged over the year;
$F_{weather} = 0.74$ from 2006-2010 mountain records, DocDB-323v1;
$F_{seeing} = 0.77$ from seeing distribution cutoff (1.5 arcsec) in DocDB-392v1;
$F_{moon} = 0.55$ adopted from DocDB-333v3 calculated range of 0.52 to 0.68.

When combined, these deliver a nominal 903 hours of on-target time per calendar year. We list the A_{tile} values derived here from the formulas above.

Verification: By construction.

L3.1.6 *The spectroscopic PSF shall be characterized for all fibers in each science exposure over the full wavelength range such that the PSF bias shall not exceed 1%.*

Motivation: The spectroscopic data reduction requires accurate knowledge of the two-dimensional PSF. Inaccuracies result in biases in the extracted spectral fluxes, noise models, and resolution matrices. One consequence is the appearance of artifacts in the spectra that can either distort absorption or emission features in object spectra, or imprint in mis-modeling of the sky-subtraction that is modeled from other fibers in the same exposure. If the PSF bias exceeds 1%, individual artifacts can exceed 1σ significance and several artifacts can conspire to masquerade as incorrect emission line redshifts ("catastrophic outliers"). Another consequence of PSF biases is to introduce spurious power in the Lyman-alpha forest.

The PSF bias is defined as:

$$\mathrm{bias} = \frac{\sum_i p_i q_i}{\sum_i q_i q_i} - 1 \tag{5}$$

where p_i is the true PSF image as a function of pixel number i and q_i is the linearly-interpolated PSF image from calibration data.

The calibration of the PSF will be measured from arc lamp spectra. If the PSF is stable on timescales of one day, then those calibration spectra can be obtained in the previous or subsequent day. If the PSF varies with time or fiber positions, then calibration data must be obtained sufficiently closely in time and/or at the requisite fiber positions. The arc lamps must have line features that are sufficiently narrow to not introduce a PSF bias, and sampled at enough wavelengths such that an interpolation between those wavelengths does not introduce a bias.

Verification: Repeated arc lamp exposures over timescales of 12 hours in the lab before delivery of the spectrographs would measure the PSF bias introduced by the spectrograph. Those same measurements at the telescope with motions of the fibers between exposures would measure the PSF bias introduced by the full system, inclusive of the spectrographs, fibers and calibration system.

L3.2 Programmatic

L3.2.1 *The 9000 square degree survey shall complete in 4 years including 6 months commissioning and validation. A goal is a 14000 square degree survey in same period but not more than 5 years plus commissioning and validation.*

Motivation: This reflects limits imposed by total operations costs.

L3.2.2 *A target galaxy and QSO catalog shall be assembled to a depth of* $r = 23.4$ *mag with astrometric errors not exceeding 100 mas RMS for each target class.*

Motivation: Required to meet target densities for LRGs (L2.2.1), ELGs (L2.3.1, QSO tracers (L2.4.1), Ly-α QSOs (L2.5.1). The astrometric errors represent the assignment of this portion of the total fiber positioning error budget.

L3.3 Environmental

L3.3.1 *Median seeing shall be assumed to be 1.1 arcsec FWHM, characterized by a galaxy Moffat profile with* β*=3.5.*

Motivation: Required at Level 4 for optics design, throughput calculation, and exposure time.

Explanation: This is the historical performance found the MOSAIC instrument, as documented in DocDB-343 (and published by Dey & Valdes 2014, PASP, 126, 296).

L3.3.2 *DESI shall meet all of its requirements while observing with zenith angles between 0 and 60°.*

Motivation: Achieving the total survey area required by L1.1 in a cost-effective survey will require some freedom in selecting target fields at a range of airmasses (or zenith angles). The survey footprint spans declinations $-20 < \delta < +84$ deg. The survey strategy can limit observations to a maximum zenith angle of 60 deg.
Explanation: The average airmass will be 1.25, with a maximum of 2.0. Required at Level 4 for optics design (atmospheric dispersion), throughput calculation, and exposure time.
Verification: The throughput for bright stars will be measured at a range of elevations during commissioning.

L3.3.3 *Telescope guiding accuracy shall be assumed to be 100 mas RMS.*

Motivation: Required at Level 4 as a component to the fiber positioning accuracy budget.
Explanation: This is the historical measured performance of the Mayall. The DESI instrument may see improved performance, as the DECam instrument on the Blanco telescope achieves 50 mas.
Verification: This will be measured by the apparent motion of guide stars in the GFAs during commissioning.

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