Preliminary AFTA-WFIRST Supernova Survey Exposure Time Calculation

Christopher Hirata

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1 Overview

This document describes the supernova survey exposure time calculations for AFTA-A. Exposure times must be allocated for imaging and spectroscopy of each tier of the survey. Additionally, tiling of each tier of the survey must be possible, and the appropriate cadence and roll angle must be possible.

This document focuses on the following strategies:

- *Option I* – Imaging (YJH) + spectroscopy (0.6–1.9 μm bandpass). The requirement is to reach SNR=20 per imaging filter and SNR=20 per synthetic $\lambda/\Delta\lambda = 4$ spectral filter every 5 days rest-frame at the peak of the light curve. (This spectral SNR is equivalent to SNR=5.66 per 12000 km/s segment of the spectrum per 5 days in the rest frame, so it also meets the Si II-based SN Ia typing criterion, assuming Si II is in band.)

- *Option II* – Same as Option I, but the spectroscopy is split using the filter wheel into 5 sub-bands (F_7ZYJH). This would require replacing the clear filter with an F_7-band filter.[1] The notional F_7-band filter is 0.60–0.77 μm, and thus includes the F_7 band down to the blue cutoff of the prism.

Other possibilities (e.g. an IFU) will be considered in future versions of this document. In each strategy, the exposure times in each imaging or spectral filter may be independently optimized.

It is expected that some of the systematics issues (sky subtraction, chromatic flats, reciprocity failure corrections) will be easier in Option II than in Option I because of the narrower range of wavelengths illuminating the focal plane at once, but this needs to be quantified.

The prism strategies are defined by visits to the SN fields once every 5 days for a duration of 2 years. Each visit has a duration of 1.25 days or 108 ks. The roll angle is changed every 45 days so that the spacecraft maintains proper Sun orientation.

The K_s-band is very far from background limited and so I have assumed it will not be used for the supernova survey. It would be used in read-noise limited (HLS-imaging) or confusion-limited (Galactic plane) programs, as well as possible GO programs.

1.1 Known issues

The document as presented here is not complete – it does not give the tiling strategy or SN yields (to be computed after we have better vetted the current set of calculations).

There are several liens against the calculations presented here:

- Have not included a factor for dead/hot pixels, or increased read noise in ramps that have a cosmic ray event during the exposure.

- Have not accounted for the quantum yield effect (stochastic multiple electrons per incident photon) at the bluer wavelengths (in the Z band down to 0.6 μm, if this effect occurs at $\lambda \lesssim \lambda_{\rm cutoff}/3$).

- Have not included the host galaxy continuum.

[1] The galaxy redshift survey prism mode is the only other mode that uses the clear position in the imaging filter wheel. It would probably have to look through the H and K_s band filters separately (or maybe just H), using these to define the bandpass. Note that HST/WFC3-IR does **not** have a clear position.

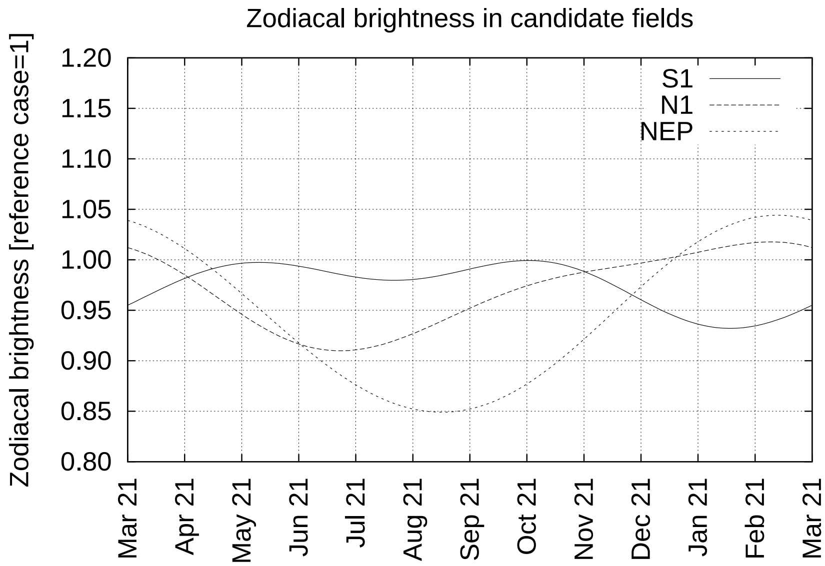

Figure 1: The predicted zodiacal light brightness as a function of time, for three candidate supernova fields. The "reference" used for calculation is taken to be 1. Time variation is computed taking into account: (i) the latitude and longitude dependence of the zodiacal light; (ii) the modulation due to distance from the Sun (Earth orbit eccentricity) with a -2.3 exponent; and (iii) a 9% modulation due to the inclination of the zodiacal cloud midplane [3].

2 Conventions and assumptions

All bands, periods of time, etc. are taken to be observer-frame in this document, unless otherwise indicated (e.g. by a subscript: $B_{\rm rest}$). The "$[F_7]ZYJH$" bands will refer to the WFIRST filters, even though these do not coincide exactly with those of other NIR facilities (in most cases, the differences are substantial). All imaging sensitivities are for point sources, since this is the relevant case for supernovae.

"Distance" D will denote the luminosity distance unless otherwise indicated, but where confusion may arise we will write $D_{\rm L}$ for emphasis.

Magnitudes are on the AB scale unless explicitly noted otherwise, in accordance with ETC conventions.

2.1 Backgrounds and related models

All calculations are performed using the WFIRST ETC [2], version 11.

Exposure time calculations are taken at 82.5° ecliptic latitude, 60° longitude relative to the Sun, a foreground dust column of $E(B-V) = 0.03$, and at the mean of the annual cycle at 1 AU from the Sun. The actual brightness observed by WFIRST will vary with time and choice of field. Examples of time variation are shown in Fig. 1 for three candidate fields: a Southern field "S1" ($\lambda = 45°$, $\beta = -82.5°$), offset from the ecliptic pole to avoid the Large Magellanic Cloud; "N1" ($\lambda = 190°$, $\beta = +84°$), offset from the ecliptic pole to reduce foreground dust; and "NEP" (the North Ecliptic Pole). Both S1 and N1 meet the dust requirement, while NEP is shown for comparison only. The S1 field would enable observations of the WFIRST deep field with Southern Hemisphere assets such as LSST.

The spacecraft was assumed to be at geocentric orbit (not L2) for this calculation, although the change in zodiacal brightness is small (less than other uncertainties in this calculation).

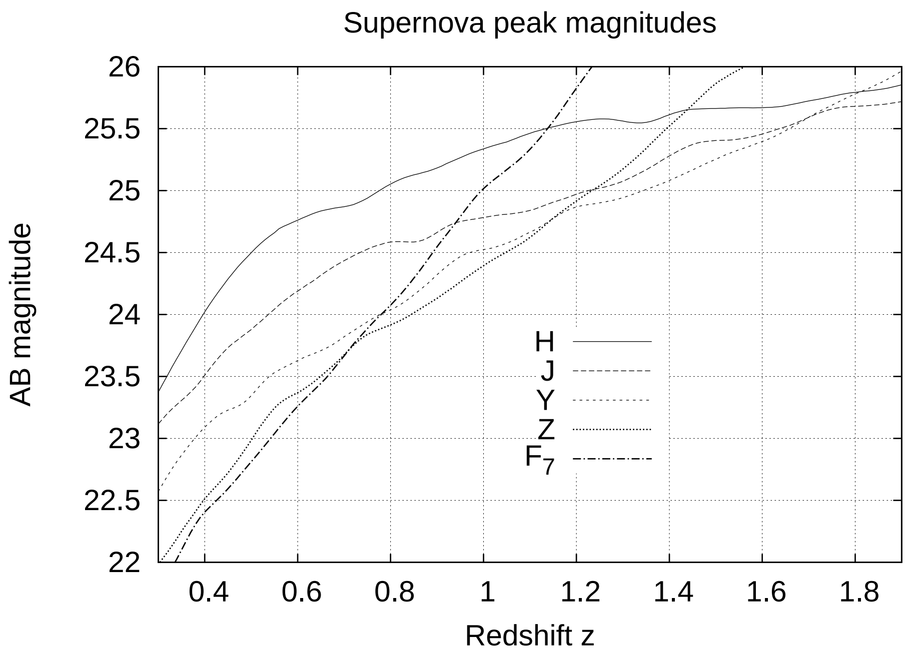

Figure 2: The AB magnitude of the fiducial supernova at peak as a function of redshift, in each of the bands considered.

2.2 Fiducial supernova

The fiducial SN Ia is taken to have peak magnitude $M_B(\text{Vega}) = -18.75$; note that 78% of the $0.2 < z < 0.5$ supernovae in the SNLS 3-year sample [1] are brighter than this value. To set the SNR requirements for photometry at the peak we have used the spectral shape of the "normal" SN Ia template[2] by P. Nugent, normalized to this absolute magnitude. In fact, most of the faint supernovae (i.e. with $M_B \sim -18.75$) will actually be red ($B - V$ at peak greater than the template). For this reason, using this template may somewhat overestimate the exposure time requirements for the reddest bands.

The AB magnitudes of the fiducial supernova at peak are shown in Fig. 2. As a simple comparison, note that the fiducial supernova has absolute magnitude $M_{B,AB} = -19.00$. At $z = 1.7$ (distance modulus 45.55), we find an apparent AB magnitude of 25.45 in the redshifted B bandpass (now centered at ~ 1.15 μm, between Y and J).[3]

2.3 Telescope and instrument performance

The following performance assumptions were used:

- An entrance pupil outer diameter after masking of 2322 mm, inner diameter of 747 mm, and 6% of the area masked by the spider.
- We use the sample-up-the-ramp mode, with one frame every 5.24 s (32 channel, 100 kHz), and use an unweighted linear fit method for the slope.[4]

[2] The template can be found at `http://supernova.lbl.gov/~nugent/nugent_templates.html`, revision 2006 March 1; based originally on Ref. [4].

[3] Note that this is $-19.00 + 45.55 - 2.5\log_{10}(1 + 1.7)$, where the last term arises because fluxes in Jy or $\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{Hz}^{-1}$ redshift more slowly than total luminosities due to compression in the frequency dimension.

[4] For the long spectroscopy exposures we should be able to reduce the exposure time by exploring alternate fitting methods that do not carry the factor of $1.2\times$ super-Poisson penalty.

- Read noise is 20 e^- rms per CDS, with a 5 e^- floor. Dark current is taken to be 0.015 e^-/pix/s.
- Line-of-sight jitter is 25 mas rms per axis.
- Telescope temperature of 273 K.
- The wavefront quality is taken as diffraction limited at 1.2 μm. Additional strategies (particularly an IFU) will be addressed in future versions of this document.
- Surface emissivities of 2% (protected Ag, PM+SM) or 1% (Au, instrument mirrors), plus a 2% contamination term distributed evenly among all optical surfaces. The instrument mirrors are cold.[5] An additional background of 0.02 e^-/p/s is assumed for internal instrument emission and filter red-leaks.[6]
- Stray light of 10% of the zodiacal brightness along the boresight.
- In-band filter transmission of 95%.
- The net throughput (excluding geometric obstructions) ranges from 45% (at $\lambda = 0.6$ μm) through 69% (at $\lambda = 1.9$ μm).

3 Imaging exposure times

The imaging exposure times are shown in Table 1. These are designed to reach SNR=20 for the fidicial supernova at peak every 5 days in the rest-frame. Since the cadence of the program is 1 visit every 5 observer-frame days, we require SNR=$20(1+z)^{-1/2}$ in each visit.

The signal-to-noise is assumed to be distributed among 4 exposures in each visit; this is the minimum that tiles efficiently and allows for image defects. The Y and J band filters will be undersampled in a single visit, even at 4 dither positions. However, since the SN Ia is known to be a point source, one should require only that the reference image (built up over many visits) be fully sampled, and that the dithering pattern suppress the intrapixel sensitivity variation to an acceptable level.

4 Spectroscopy exposure times

The spectroscopic exposure times are shown in Table 2. The required SNR per visit per 2000 km/s was determined by scaling the requirement of SNR=20 per $\lambda/\Delta\lambda = 4$ synthetic filter per 5 days rest frame at peak to SNR per visit. A further factor of $\sqrt{2}$ was included to account for the noise in the reference spectrum, which is acquired exactly 1 year before (or after) as part of the regular supernova survey. This leads to

$$\text{SNR(per visit per 2000 km/s)} = 20 \left[\sqrt{\frac{5 \text{ days}}{5(1+z) \text{ days}}}\right] \left[\sqrt{\frac{2000 \text{ km/s}}{c/4}}\right] \left[\sqrt{2}\right]. \tag{1}$$

The 2000 km/s reference was chosen because the AFTA-A dispersion is 2000 km/s/pixel.

While the noise level (in magnitudes per pixel) is close to flat across even the wide bandpass (the variation from 0.68–1.91 μm is only 0.2 magnitudes), the spectrum of a SN Ia contains many prominent resonance lines of the common metals. Therefore the SNR varies rapidly with wavelength, and requiring a certain SNR in the middle of an absorption feature will result in much longer exposure times than requiring the same SNR in the adjacent "continuum." Moreover, the SNR at $\lambda \lesssim 0.38$ μm will be very small. Therefore the SNR requirement was implemented as follows:

- Only the rest-frame visible, defined as 0.385–0.7 μm, is considered.

[5] The input to the ETC is 210 K for the first four mirrors (this is cold enough to be irrelevant).
[6] For a 2.5 μm cutoff detector, a filter red-leak of 10^{-4} transmission near cutoff would use 0.006 e^-/p/s of this allocation.

Table 1: The required exposure times per visit for the supernova imaging.

Redshift	SNR per visit	Y Exp. time	Y mag	J Exp. time	J mag	H Exp. time	H mag
0.20	18.26	4× 21 s	21.79	4× 26 s	22.41	4× 26 s	22.57
0.30	17.54	4× 26 s	22.57	4× 37 s	23.12	4× 42 s	23.37
0.40	16.90	4× 37 s	23.09	4× 47 s	23.51	4× 63 s	24.02
0.50	16.33	4× 42 s	23.34	4× 58 s	23.88	4× 86 s	24.50
0.60	15.81	4× 47 s	23.63	4× 68 s	24.19	4× 105 s	24.76
0.70	15.34	4× 52 s	23.82	4× 79 s	24.43	4× 110 s	24.87
0.80	14.91	4× 63 s	24.04	4× 84 s	24.59	4× 126 s	25.05
0.90	14.51	4× 73 s	24.32	4× 89 s	24.66	4× 136 s	25.18
1.00	14.14	4× 79 s	24.52	4× 94 s	24.78	4× 152 s	25.34
1.10	13.80	4× 89 s	24.66	4× 94 s	24.84	4× 168 s	25.46
1.20	13.48	4× 100 s	24.87	4× 105 s	24.97	4× 178 s	25.56
1.30	13.19	4× 105 s	24.94	4× 110 s	25.07	4× 173 s	25.56
1.40	12.91	4× 111 s	25.08	4× 126 s	25.28	4× 178 s	25.61
1.50	12.65	4× 126 s	25.25	4× 136 s	25.40	4× 183 s	25.66
1.60	12.40	4× 141 s	25.40	4× 141 s	25.46	4× 183 s	25.67
1.70	12.17	4× 162 s	25.59	4× 157 s	25.59	4× 189 s	25.72

- For Option II, in each of the 5 bandpasses (F_7ZYJH), the SNR is set for the mean signal in the intersection of that bandpass with the 0.385–0.7 μm rest-frame range. (If this range is the empty set, then we do not set a sensitivity requirement in that bandpass. In practice in the deeper tiers of a survey this means there is noisy coverage at bluer wavelengths because of the requirement to measure the lower-z SNe; see Fig. 4 for an example of an outcome of this.) The sensitivity required is shown in Fig. 3.
- For Option I, the exposure time is set to achieve the Option II requirement in the most difficult of the 5 bandpasses.

In order to limit cosmic ray events, exposures were required to be no longer than 1200 s. This corresponds to a probability of 10% to receive a cosmic ray hit within 2 pixels of any point in the image at the interplanetary rate of 5 cm^{-2} s^{-1}. In a lower orbit such as GEO this rate may increase depending on the effectiveness of shielding.

As an example of the inputs to the supernova spectroscopic exposure time calculation, let us consider the case of a $z = 1.7$ supernova in H band for Option II. We find the following parameters from ETC v11 outputs:

- Background flux = 0.501 e^-/p/s (0.340 from the sky, 0.146 telescope and instrument thermal backgrounds, 0.015 dark current).
- In $t = 1131$ s, the total background flux is 567 e^-/p; the noise variance is 720 $(e^-)^2$/p, which is dominated by the sample-up-the-ramp super-Poisson term ([681 $(e^-)^2$/p]. The read noise in this long exposure is a minor term.
- At the band center (1.68 μm) the noise-equivalent effective width of a spectral trace is 4.46 pixels (0.49 arcsec).[7]
- At 2000 km/s per spectral pixel, at the band center, the count rate is 0.225 e^-/s per spectral pixel for a 1 μJy source, excluding light lost to diffraction spikes.

[7]The noise-equivalent width is defined as the width of a perfect tophat trace that would have the same SNR as the real trace profile. For a Gaussian, the noise-equivalent width is 1.5×FWHM; the prefactor is larger for more realistic trace profiles.

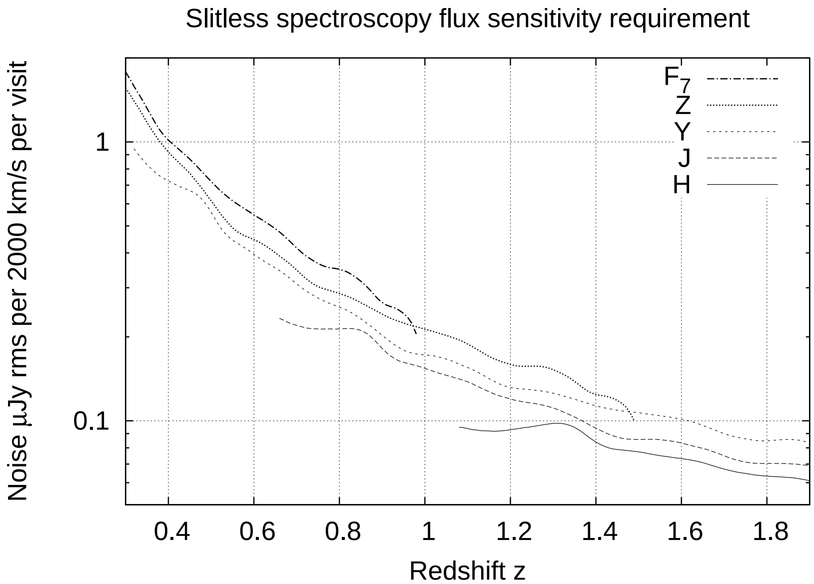

Figure 3: The required spectral sensitivity for Option II in 1 visit in each spectral range.

- The consequent SNR per spectral pixel per exposure is then $0.225 S_{\mu\mathrm{Jy}} \times 1131 \div \sqrt{4.46 \times 720}$ or $4.49 S_{\mu\mathrm{Jy}}$.
- For an $H_{\mathrm{AB}} = 25.72$ or 0.19 μJy source, in 11 exposures, we reach SNR$= 4.49 \times 0.19\sqrt{11} = 2.8$ per spectral pixel.

In Figure 4, we show examples of simulated *coadded* 15-day rest-frame SN spectra in a deep tier of the survey designed to reach the above requirements at $z \leq 1.7$.

References

[1] J. Guy et al., *Astron. Astrophys.* **523**:7 (2010)

[2] C. Hirata et al., preprint, arXiv:1204.5151 (2012)

[3] C. Leinert et al., *Astron. Astrophys. Supp.* **127**:1 (1998)

[4] P. Nugent, A. Kim, S. Perlmutter, *Proc. Astron. Soc. Pac.* **114**:803 (2002)

Table 2: The required exposure times per visit for the supernova spectroscopy. Note that in Option II, the spectroscopy is split into spectral bands: these are then stitched together, analogous to the arms of a conventional spectrograph (except that they are acquired in series). The "SNR per visit" does **not** include the penalty from the reference exposures.

Redshift	SNR per 2000 km/s per visit	Option I	Option II				
			F_7	Z	Y	J	H
0.20	4.22	4× 36 s	4× 36 s	4× 36 s			
0.30	4.05	4× 62 s	4× 57 s	4× 62 s			
0.40	3.90	4× 130 s	4× 83 s	4× 89 s	4× 104 s		
0.50	3.77	4× 183 s	4× 109 s	4× 120 s	4× 130 s		
0.60	3.65	4× 314 s	4× 136 s	4× 162 s	4× 178 s		
0.70	3.54	4× 917 s	4× 169 s	4× 209 s	4× 230 s	4× 324 s	
0.80	3.44	4× 969 s	4× 199 s	4× 256 s	4× 288 s	4× 335 s	
0.90	3.35	5×1068 s	4× 267 s	4× 314 s	4× 392 s	4× 424 s	
1.00	3.27	7×1058 s		4× 370 s	4× 497 s	4× 544 s	
1.10	3.19	17×1178 s		4× 440 s	4× 587 s	4× 655 s	6×1063 s
1.20	3.11	17×1199 s		4× 565 s	4× 775 s	4× 833 s	6×1087 s
1.30	3.05	16×1152 s		4× 602 s	4× 838 s	4× 953 s	5×1168 s
1.40	2.98	21×1189 s		4× 848 s	4×1011 s	5×1053 s	7×1137 s
1.50	2.92	25×1178 s			4×1121 s	6×1058 s	8×1168 s
1.60	2.86	28×1173 s			5×1011 s	6×1116 s	9×1163 s
1.70	2.81	33×1184 s			6×1063 s	7×1173 s	11×1131 s

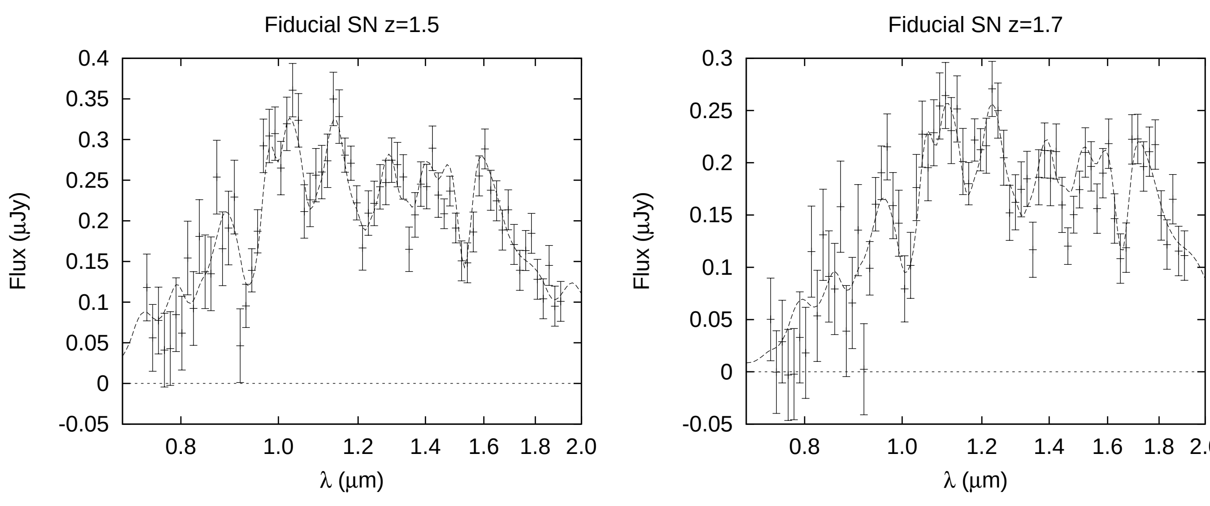

Figure 4: Spectra of sample supernovae at $z = 1.5$ and $z = 1.7$ using Option II. These are set to the depth of the deep tier: 4×848 s (Z), 6×1063 s (Y), 8×1173 s (J), and 11×1131 s (H) *per visit*. The spectra shown are *co-added* over 15 days of the rest frame (7–8 visits) from peak -5 days to peak $+10$ days, with the reference spectrum noise included. The "data" points are binned by 2 spectral pixels. [Note: These were simple 1D spectra smoothed to the expected resolution and with appropriate noise added, not from a full instrument simulation.]