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Photometric Calibration of WFPC2 Linear Ramp Filter Data in SYNPHOT

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ABSTRACT

We discuss derivation and use of the SYNPHOT Linear Ramp Filter throughput table, which provides a preliminary photometric calibration with accuracy ~3%.

1. Introduction

The SYNPHOT synthetic photometry package has become one of the main tools for performing photometric calibration of WFPC2 data. In this report we derive a SYNPHOT filter transmission table for the Linear Ramp Filters (LRFs). This new table, together with system and CCD efficiencies already in SYNPHOT, provides a preliminary photometric calibration of the LRFs.

This table has two principal ingredients. The first is the TRANS LRF table, which maps the observer's central wavelength onto a particular spot on the LRF filter glass. (The TRANS LRF table can be found in Biretta, et al., 1996a as Table 13; an abridged version appears in Tables 3.7 and 3.8 of the *WFPC2 Handbook*, Biretta, et al., 1996b) The second ingredient is a set of ground-based calibrations which give the LRF filter transmissions as a function of position on the filter glass. In this report we discuss how the TRANS LRF table and the laboratory transmission measurements are used together to generate the SYNPHOT LRF table. Sections 2 and 3 review the general properties of the LRFs and the lab measurements made at JPL. Section 4 describes how the table is computed. Section 5 describes how to obtain and install the new table, and Section 6 describes how to use this table for photometric calibration.

Our experience with other WFPC2 filters indicates that the lab filter calibration, together with on-orbit determinations of CCD and system throughput, should provide photometric calibration accurate to ~3%, which is sufficient for most purposes. In the future, standard

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[1] Copies of this report may be obtained from the Science Support Division, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore MD 21218, by e-mail to help@stsci.edu, by anonymous FTP to stsci.edu directory instrument_news/WFPC2, and by WWW at http://www.stsci.edu/instruments.html

stars will be observed through the LRFs to verify the predicted throughputs.

All SYNPHOT users are advised to obtain a copy of the current (March 1995) *SYNPHOT User’s Guide* by sending e-mail to `help@stsci.edu`.

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2. Review of LRF Filter Properties

The WFPC2 Linear Ramp Filters (LRFs) offer a narrow band imaging capability which is tunable from 3710Å to 9762Å with bandpass FWHM $\Delta\lambda/\lambda \sim 0.013$. The LRF filter set contains four narrow band interference filters (named FR418N, FR533N, FR680N, and FR868N), and each filter contains four ramps (numbered #1 through #4) whose central wavelength varies as a function of position on the filter surface. In addition, each filter can be rotated to four different partial rotations of the filter wheel (-33˚, -18˚, 0˚, or +15˚); this rotation is used to move wavelengths which would otherwise fall outside the CCDs into the region imaged by the CCD detectors.

An observer using the LRFs is asked only to specify the desired "central wavelength" on the Phase II proposal; the aperture and filter is entered simply as "LRF." During proposal implementation, the TRANS program must convert the user-specified wavelength into a correct filter selection, and must also calculate a positional offset that will place the target at the correct location on the ramp filter. This is done by finding the requested central wavelength in the TRANS LRF lookup table, and then interpolating the pointing offset from the two nearest entries in the table. The table also specifies the filter, filter wheel rotation, and CCD to be used.

3. Ground-based Transmission Measurements for the LRFs

Wavelength and transmission calibration is provided by a set of lab measurements made on the flight filters at JPL. A complete description of the LRF transmission measurements can be found in Evans (1992). A monochrometer with a narrow slit was used to provide illumination, and a micrometer provided position information. The transmission profile was measured at five equally spaced points along the length of each ramp. The resulting data were later integrated over an annular aperture to simulate the out-of-focus OTA beam passing through the filter. This integration largely defines the bandpass shape, and results in highly symmetric transmission curves.

Munson functions of the following form were then fitted to the integrated transmission curves:

$$T = \frac{T_0}{1 + (1-a)x^2 + a(1-b)x^4 + ab(1-c)x^6 + abcx^8} \qquad (1)$$

where

a, b, and c are shape parameters ($0 \le a, b, c \le 1$),

T_0 is the peak transmission of the passband, $T = T_0$ at $x = 0$,

x is related to wavelength by

$$x = \frac{(w - w_0)}{HWHM} \qquad (2)$$

and w_0 is the center wavelength.

The shape parameters, a, b, and c, and the parameters T_0, w_0, and $HWHM$ were then fitted to polynomial functions of physical distance Y in inches along the ramp:

$$Parameter = A_0 + A_1 Y + A_2 Y^2 + A_3 Y^3 \qquad (3)$$

Table 1 gives the coefficients in this equation. These coefficients are identical to those listed in Evans (1992) and in WFPC2 Handbook (V.3.0) Tables 3.3 to 3.5, except for the parameter Y. For consistency with the TRANS LRF table, we instead use the linearized wavelength relations given by Biretta, et al. (1996a), which are typically accurate to 0.3Å:

$$Y = A_0 + A_1 w_0 \qquad (4)$$

The coefficients in equation (4) are derived from $C_{1,2}$ and $C_{1,4}$ given in Table 3 of Biretta, et al. (1996a):

$$A_0 = C_{1,2}|C_{1,4}|$$

$$A_1 = |C_{1,4}|$$

and are listed in Table 1.

Table 1: Polynomial Coefficients for Parameters.

Filter / Ramp #	*Parameter*	A_0	A_1	A_2	A_3
FR418N #1	Y	-26.1083	.00713888	.0000	.0000
	w_0	3657.7	138.7	.6178	.0000
	T_0	-.01667	.2188	.04138	-.03489
	$HWHM$	21.95	-.8347	2.143	.0000
	a	.2120	.002857	.002596	.0000
	b	1.181	-.8138	.3535	.0000
	c	.3301	-.3715	.3825	.0000
FR418N #2	Y	-24.2554	.00625704	.0000	.0000
	w_0	3876.9	158.6	.5472	.0000

Table 1: Polynomial Coefficients for Parameters.

Filter / Ramp #	*Parameter*	A_0	A_1	A_2	A_3
	T_0	.1660	.2288	-.1080	.004005
	HWHM	21.50	3.315	-.7079	.0000
	a	.1592	-.003687	-.0008497	.0000
	b	.7938	.2355	-.09124	.0000
	c	.9306	.01366	.007458	.0000
FR418N #3	*Y*	-24.7145	.00598254	.0000	.0000
	w_0	4130.5	168.8	-.7389	.0000
	T_0	.1352	.6200	-.5226	.1529
	HWHM	22.09	1.306	-.1181	.0000
	a	.2300	.05586	-.03044	.0000
	b	1.096	-.3185	.1396	.0000
	c	1.276	-1.279	.5721	.0000
FR418N #4	*Y*	-23.4440	.00536340	.0000	.0000
	w_0	4371.3	185.8	.2913	.0000
	T_0	.3189	.1287	-.01160	-.001712
	HWHM	25.62	1.015	.1161	.0000
	a	.3123	-.2055	.09535	.0000
	b	.9222	.1167	-.04673	.0000
	c	1.033	-.1356	.05660	.0000
FR533N #1	*Y*	-26.7670	.00572115	.0000	.0000
	w_0	4677.7	177.3	-1.125	.0000
	T_0	.5450	-.3612	.3623	-.1281
	HWHM	25.67	.3168	.8873	.0000
	a	-.009839	.4644	-.2039	.0000
	b	.31511	.9473	-.4516	.0000
	c	-.3379	2.788	-1.346	.0000
FR533N #2	*Y*	-24.6600	.00498393	.0000	.0000
	w_0	4948.4	199.2	.6484	.0000
	T_0	.4546	.4188	-.5456	.1548
	HWHM	32.10	-1.204	3.171	.0000
	a	.1678	-.02726	.09521	.0000
	b	.9345	.1935	-.1244	.0000
	c	.9571	.02919	-.009393	.0000
FR533N #3	*Y*	-24.5038	.00465985	.0000	.0000
	w_0	5257.3	217.9	-1.481	.0000
	T_0	.4944	-.1714	.1890	-.0631
	HWHM	34.03	5.078	-1.347	.0000
	a	.3851	-.06264	.003163	.0000
	b	.5605	.6642	-.2751	.0000

Table 1: Polynomial Coefficients for Parameters.

Filter / Ramp #	*Parameter*	A_0	A_1	A_2	A_3
	c	.9665	.05543	-.03654	.0000
FR533N #4	Y	-25.5182	.00455886	.0000	.0000
	w_0	5596.9	220.9	-.6938	.0000
	T_0	.5058	-.2715	.3203	-.1230
	HWHM	35.06	-2.856	2.382	.0000
	a	.06553	.2253	-.08275	.0000
	b	1.043	-.1190	.02889	.0000
	c	1.162	-.4910	.2059	.0000
FR680N #1	Y	-21.8962	.00370137	.0000	.0000
	w_0	5916.0	269.4	.3460	.0000
	T_0	.1198	1.005	-.4015	-.00162
	HWHM	41.50	-5.873	4.038	.0000
	a	.1743	-.05050	.06481	.0000
	b	.8320	.3326	-.1858	.0000
	c	.9682	-.09110	.05122	.0000
FR680N #2	Y	-22.6919	.00360750	.0000	.0000
	w_0	6290.8	275.6	.7184	.0000
	T_0	.7918	-.02034	.1086	-.05945
	HWHM	39.48	2.120	.3703	.0000
	a	.05596	.3034	-.1333	.0000
	b	1.017	-.27026	.04560	.0000
	c	.7244	.8326	-.5107	.0000
FR680N #3	Y	-22.0719	.00330755	.0000	.0000
	w_0	6673.5	301.6	.3321	.0000
	T_0	.9494	-1.008	1.161	-.3777
	HWHM	42.81	.8193	.4269	.0000
	a	.1038	.09020	-.02747	.0000
	b	.8415	.3045	-.1930	.0000
	c	1.017	-.1732	.07463	.0000
FR680N #4	Y	-24.7447	.00346462	.0000	.0000
	w_0	7141.9	289.3	-.2999	.0000
	T_0	.4823	.4479	-.07484	-.05868
	HWHM	44.72	.8952	-.0756	.0000
	a	.1612	-.01167	.01355	.0000
	b	.2708	1.077	-.4757	.0000
	c	.9941	-.02694	.01685	.0000
FR868N #1	Y	-23.2685	.00308029	.0000	.0000
	w_0	7555.5	320.4	1.906	.0000
	T_0	.7524	-.3328	.4543	-.1343

Table 1: Polynomial Coefficients for Parameters.

Filter / Ramp #	Parameter	A_0	A_1	A_2	A_3
	HWHM	49.32	1.742	.4914	.0000
	a	.2958	-.3877	.2465	.0000
	b	1.321	-.9156	.3666	.0000
	c	.3762	1.668	-.9499	.0000
FR868N #2	Y	-22.9766	.00286673	.0000	.0000
	w_0	8014.3	350.5	-.7500	.0000
	T_0	.8204	-.3368	.3815	-.1057
	HWHM	54.17	1.579	.2196	.0000
	a	.05832	.7525	-.3625	.0000
	b	.4582	.8433	-.4350	.0000
	c	.6422	.3247	-.1593	.0000
FR868N #3	Y	-22.6085	.00265657	.0000	.0000
	w_0	8510.7	375.6	.3706	.0000
	T_0	.5817	-.1920	.4517	-.1627
	HWHM	55.19	-.7459	1.433	.0000
	a	.5422	-.2444	.03545	.0000
	b	1.420	-1.176	.4814	.0000
	c	.4257	-.2522	.1777	.0000
FR868N #4	Y	-23.2142	.00256976	.0000	.0000
	w_0	9034.3	387.2	.8722	.0000
	T_0	.6241	.2403	-.1230	.02829
	HWHM	59.69	2.167	-.1996	.0000
	a	.2376	-.01879	-.00864	.0000
	b	.9670	.02456	-.00477	.0000
	c	.7829	.03750	.02393	.0000

4. Calculation of the SYNPHOT LRF Table

We begin by discussing the format of the table, and the way it is utilized by the SYNPHOT program. After that, we describe in depth how the elements of the table are computed.

4.1 Format and utilization of the SYNPHOT LRF table

SYNPHOT integrates the detected countrate in many wavelength intervals to model the overall countrate measured by an observer. At each wavelength interval the countrate is computed as the product of the target countrate, the transmissions of the OTA, WFPC optics and filter(s), and the CCD response. For standard filters the SYNPHOT filter transmission tables are simply one-dimensional tables listing wavelengths and the transmissions at those wavelengths. In contrast, the LRF filters are tunable to many different wavelengths, and hence its SYNPHOT transmission table is two-dimensional. The dimensions are wavelength setting (i.e. wavelength requested on the Phase II proposal, running across the rows), and wavelength / transmission as in the ordinary filters (running down the columns).

Table 2 shows portions of the final SYNPHOT LRF table, and serves to illustrate its format in more detail. In essence, each column in the table contains the entire transmission curve for a given central wavelength (WAVE#xxxx) which an observer would specify on the Phase II proposal. This is equivalent to the transmission curve at a given physical location on the LRF filter glass. The first entry in each row gives the wavelength, and the other entries give the transmission values at that wavelength. For example, as we go down the column titled WAVE#3709.999 we see that the transmission peaks at ~0.0698 for WAVELENGTH~3710Å. The next column to the right, which is titled WAVE#3714.162, has a peak transmission ~0.0768 for WAVLENGTH~3714Å, and so forth.

Table 2: Portions of SYNPHOT LRF table.

WAVELENGTH	WAVE#3709.999	WAVE#3714.162	WAVE#3718.329	...	...
1.0000	0.	0.	0.	...	(998 cols)
3000.0000	0.	0.	0.	...	...
3001.5000	0.	0.	0.	...	...
3003.0007	0.	0.	0.	...	...
...	...	...	...	...	...
3516.8740	0.	0.		...	...
3518.6331	4.1519e-8	0.	0.	...	...
3520.3921	4.4670e-8	4.6018e-8	0.	...	...
...	...	...	...	...	...
3708.2471	0.069466	0.072649	0.071765	...	...
3710.1011	0.069814	0.074791	0.075431	...	...
3711.9561	0.069380	0.076198	0.078589	...	...
3713.8120	0.068193	0.076787	0.081103	...	...
3715.6689	0.066323	0.076519	0.082843	...	...
3717.5271	0.063870	0.075409	0.083709	...	...
3719.3860	0.060948	0.073525	0.083644	...	...
...	...	...	...	...	...
(2776 rows)	...	...	...	...	...

Observers specify LRF settings in SYNPHOT by placing LRF#xxxx in the PHOTMODE, where xxxx is the central wavelength specified on the Phase II proposal. SYNPHOT will look amongst the column headers in the table until it finds a pair of WAVE#yyyy entries which bracket the wavelength specified in the PHOTMODE. Next it looks through the first column of the table, the WAVELENGTH column, until it finds a pair of values bracketing the wavelength at which the throughput value is needed. Finally, SYNPHOT does a two-dimensional linear interpolation between the four throughput values surrounding the required WAVE# and WAVELENGTH point.

4.2 Calculation of the SYNPHOT LRF table

We begin with details of the table structure and layout. We have used logarithmic steps in both WAVE#xxxx and WAVELENGTH when creating the table, since this maximizes the accuracy for a given table size. The necessity of storing the table in FITS format within the HST archive limits the number of columns to a maximum of 1000. Hence the WAVE# values are stepped according to

$$WAVE(n+1) = 1.001122 \times WAVE(n) \tag{5}$$

which leads to 998 steps in WAVE#xxxx between the lowest (WAVE#3710) and highest (WAVE#9762) settings, when extra values for jumps, etc. are included (as discussed below). There is no limit to the number of rows, and we have therefore used finer logarithmic steps in WAVELENGTH:

$$WAVELENGTH(n+1) = 1.0005 \times WAVELENGTH(n) \tag{6}$$

which leads to 2776 rows.

There are also places where sudden jumps are required in the throughput values. These occur at the start and end of wavelength runs in the TRANS LRF table, where either the ramp segment, filter, or filter rotation suddenly changes. To handle these we have made two WAVE#xxxx entries stepped by only 0.001Å at these boundaries. For example, central wavelengths of 3800Å or less are mapped onto filter FR418N, ramp #1, rotation 0˚. But central wavelengths above 3800Å map onto filter FR418N, ramp #1, rotation -33˚. Hence we have made two columns in the SYNPHOT LRF table near this wavelength -- one at WAVE#3800.000 which ends the first filter setting, and one at WAVE#3800.001 which starts the second setting. Because of this, SYNPHOT LRF users must specify their wavelength to the nearest 0.01Å. Specifying the wavelength to more than two decimal places will cause errors at these jumps.

Another important detail is the handling of “vignetted” settings of the LRFs. These are wavelengths where, for one reason or another, the optimal location on the filter glass cannot be reached (for example, filter areas which lie outside the field imaged by the CCDs). Instead, these wavelengths are observed at the closest available setting, and hence the overall transmission curve will be offset slightly in wavelength from the optimal curve for the requested wavelength. Accordingly, the wavelength requested by the observer will not be at the peak of the transmission curve, but rather will be offset slightly from the peak, which will generally imply a small reduction in transmission. Handling of these vignetted regions in the SYNPHOT LRF table is very simple — as with unvignetted wavelengths, the transmission curve is set to that appropriate for the physical location on the filter glass used for the observation. As should be apparent, vignetted wavelength ranges in the TRANS LRF table result in identical adjacent columns in the SYNPHOT LRF table, with only the WAVE# changing. This occurs is because a single physical location on the filter glass (with a single transmission curve) is assigned to multiple wavlengths (WAVE#) once the optimal location on the filter can no longer be reached.

Actual calculation of the table proceeds as follows. One takes each line of the TRANS LRF table, and steps through the central wavelength range for that line using equation (5), starting at the low wavelength end (plus 0.001Å), and ending at a the upper wavelength value. At each wavelength step, one writes a column titled WAVE#xxxx in the LRF table, where xxxx is the central wavelength. The throughput values in the column are computed using the following steps:

> Set w_0 = xxxx, where xxxx is the value in WAVE#xxxx.
>
> Obtain the filter and ramp# for wavelength w_0 from the TRANS LRF table.
>
> Compute Y from w_0 using equation (4) and appropriate “parameter Y” entries in Table 2 for that filter and ramp#.
>
> Compute a, b, c, T_0, and $HWHM$ from Y using equation (3) and the appropriate polynomial coefficients in Table 1 for the filter and ramp# specified by the TRANS LRF table.
>
> Step down the column starting with WAVELENGTH = w = 3000Å and using equation (6), computing a transmission value T at each step using equations (1) and (2), until the complete transmission curve for that central wavelength setting is obtained.

Separate rows for 1Å and 999999Å are introduced at the top and bottom of the table, to prevent erroneous extrapolations at very small and large wavelengths. Errors caused by quantization and linear interpolation in the table are less than 1% at all wavelengths. Sample transmission curves are shown in the Appendix.

5. Obtaining and Installing the SYNPHOT LRF Table

If your local SYNPHOT tables (e.g., wfpc2 optics, dqe, filter throughputs, etc.) were updated July 1995 or later, the only new files that will need to be retrieved are the new LRF table and the new *graph* and *comp* tables which point to the new LRF table. Note: if your local tables predate July 1995, retrieve just the README file from the wfpc2 directory specified below, for detailed instructions on updating all wfpc2-related throughput tables at once. Retrieval can be done via ftp (commands are given in **`boldface`** on the left):

```
ftp stsci.edu
login anonymous          give email address as password
binary                   set transfer mode to binary
```

```
cd cdbs/cdbs2/comp         directory for all graph and comp tables
ls hstgraph*               list out graph tables
get hstgraph_960208a.tab  or any graph table later than this Feb 8,1996 table1
ls hstcomp*
get hstcomp_960208a.tab   or any comp table later than this Feb 8,1996 table1
cd wfpc2                   contains all wfpc2-related tables
get wfpc2_lrf_002.tab      new lrf table, old file was *001.tab
quit
```

That’s it. Once retrieved, the files need to be placed in their respective directories at your local site: `cdbs/comp` (graph and comp tables) and `cdbs/comp/wfpc2` (lrf table). Two other useful checks to run, to verify that the LRF component is installed correctly at your site:

1) The IRAF refdata parameter set should be set, either by executing an `unlearn refdata` at the IRAF prompt, or by using `epar` to examine and alter the parameter set. To point all the SYNPHOT tasks at the most recent *comp* and *graph* table files, refdata should be set as follows (text shown in **`boldface`** is entered by user):

```
   epar refdata
PACKAGE = synphot
TASK = refdata
   (area   =          45238.93416) Telescope area in cm^2
   (grtbl  =    crcomp$hstgraph_*) Instrument graph table
   (cmptbl =     crcomp$hstcomp_*) Instrument component table
   (mode   =                    a)

:quit
```

Including the literal "`_*`" in the table name fields will direct the tasks to use the most recent *comp* and *graph* tables in your local `cdbs/comp` directory (i.e., with subsequent synphot table updates, you won’t need to change refdata).

2) Check that the new LRF table is being accessed, for example, using the showfiles task:

```
showfiles "wfpc2,4,a2d7,lrf#3750"
#Throughput table names:
crotacomp$hst_ota_005.tab
crwfpc2comp$wfpc2_optics_003.tab
crwfpc2comp$wfpc2_lrf_002.tab[wave#]   <--should see wfpc2_lrf_002.tab
crwfpc2comp$wfpc2_dqewfc4_002.tab
crwfpc2comp$wfpc2_a2d7wf4_002.tab
```

Note that specifying the filtername (e.g. FR418N) in the OBSMODE is not necessary; the pipeline (CALWP2) currently includes the filter in the PHOTMODE (keyword in the image header, equivalent to obsmode in SYNPHOT parameter sets), but it does not

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[1] Since all instruments use these `hstgraph*` and `hstcomp*` tables, many synphot updates do not affect wfpc2 throughput data (e.g., the later Feb 9, 1996 update did not include wfpc2-related changes).

include any additional throughput component. The showfiles command will report a message to this effect:

```
showfiles "wfpc2,4,a2d7,fr418n,lrf#3750"
WARNING Instrument mode keywords not used: fr418n
#Throughput table names:
crotacomp$hst_ota_005.tab
crwfpc2comp$wfpc2_optics_003.tab
crwfpc2comp$wfpc2_lrf_002.tab[wave#]
crwfpc2comp$wfpc2_dqewfc4_002.tab
crwfpc2comp$wfpc2_a2d7wf4_002.tab
```

6. How to Perform LRF Photometric Calibration with SYNPHOT

Prior to making photometric measurements, the LRF images should be flat fielded with a narrow band filter flat observed at a nearby wavelength. As of this writing, this is not automatically done during the "pipeline" calibration. For example, near 5000Å one would use a flat observed through the F502N filter. The WFPC2 WWW pages at address `http://www.stsci.edu/ftp/instrument_news/WFPC2/wfpc2_top.html` should be consulted for the latest flat field reference files. A suitable flat should be obtained from the HST data archive, and then *multiplied* into the LRF images. Table 3 lists the current narrow band flats, but observers should also check the WWW pages for updated versions of these flats. Wide band filter F791W is included to avoid a large gap at those wavelengths.

Table 3: Recommended Flat Fields

λ(Å)	FILTER NAME	FLAT FIELD FILE	MODE
3750	F375N	e3809349u	full
3900	F390N	e380934eu	full
4370	F437N	e380934ju	full
4690	F469N	e380934su	full
4870	F487N	e3809351u	full
5020	F502N	e3809354u	full
5880	F588N	e3914337u	full
6310	F631N	e391433gu	full
6560	F656N	e391433ju	full
6580	F658N	e391433lu	full
6730	F673N	e391433ru	full
7910	F791W	e391434bu	full
9530	F953N	e391434mu	full

We strongly recommend using narrow band filter flats, since these are insensitive to the spectral variations in the flat field light source. If instead, one were to use a flat taken through the LRF, a very accurate spectrum would be needed for the light source so that its spectral variations could be corrected during photometric calibration. Using a narrow band flat eliminates these uncertainties. In addition, the F418N LRF filter also contains a number of pinholes; while these usually have no impact on science images, they seriously corrupt flats taken through that filter. For these reasons we recommend flat fielding with one of the narrow band flats listed in Table 3. Tests indicate they should give results accurate to a few percent (2% to 3%).

After flattening the data, count levels should be measured for the target in the usual manner. Unlike the normal filters, the target location for the LRFs depends on the wavelength specified in the Phase II proposal, and may not be obvious if the target is faint. The target locations (CCD and pixel numbers) can be estimated using Tables 3.7 and 3.8 in the *WFPC2 Handbook* (V.3.0 or later), or the *LRF Calculator Tool* on the WFPC2 WWW pages.

The conversion from target counts to target flux is performed using SYNPHOT. The CALCPHOT task in SYNPHOT will compute the expected count rate for a variety of model targets, and hence provides the necessary scaling from counts to flux. There are three essential ingredients for this calculation: an OBSMODE which describes the instrumental parameters, a WAVETAB which lists the wavelength intervals used for the calculation, and a SPECTRUM containing a model of the target spectrum.

Observers specify LRF settings in the OBSMODE by including **`LRF#xxxx`**, where xxxx is the central wavelength specified on the Phase II proposal. It is imperative that the number from the Phase II proposal be used, since this selects the filter transmission curve. The value from the Phase II must be used, regardless of whether the LRF setting is vignetted, or whether the emission line was really at a different wavelength than specified on the Phase II. Also, as discussed in Section 4, the central wavelength must be specified to two decimal places or less (e.g. **`5069.34`** or **`5069`**, but **not** as **`5069.343`**). The total HST and WFPC2 efficiencies should also be included by specifying **`wfpc2,3.`** The "**`3`**" implies CCD WF3, but the identical results will be obtained regardless of which CCD is specified. Also, **`a2d7`** or **`a2d15`** should be given depending on whether the gain was set to 7 or 14, respectively, during the observation. Hence the OBSMODE would be specified as (e.g.):

```
obsmode = wfpc2,3,lrf#5007,atd7
```

where the central wavelength is 5007Å in this example. The LRF bandpass, either with or without the OTA+WFPC2+CCD efficiencies, can be plotted with the SYNPHOT PLBAND task as shown in the Appendix.

The default WAVETAB or wavelength table used by SYNPHOT can have steps which are too coarse to accurately integrate a narrow filter, such as the LRFs. This can be remedied by using the GENWAVE command in SYNPHOT to custom-design a wavelength table. In general, 1Å steps should be more than sufficient for the LRFs, although the wavelength steps must also be fine enough to well-sample any narrow lines in the target spectrum. The name of this table is then given as the WAVETAB parameter in the various SYNPHOT tasks.

Here is an example of running GENWAVE. First we start IRAF and load the SYNPHOT package, and then we run GENWAVE:

```
cl

stsdas

hst_calib

synphot

genwave wavelen.tab 1000. 12000. 1.
```

This produces a table from 1000Å to 12000Å in 1Å steps.

We next discuss the specification of model spectra for emission line, stellar, and powerlaw targets.

6.1 Emission line spectra

Modeling of spectral lines will generally require use of the either the BOX or GAUSS passband functions to generate a model line profile. While the *SYNPHOT User's Guide* describes these as part of the OBSMODE, or instrumental parameters, they can also be used to specify a target spectrum. For example, we can multiply a box passband by a constant spectrum to obtain a box-shaped emission line:

```
spectrum = box( 5007, 10) * unit(1.0e-15,flam)
```

which describes a box emission line 10Å wide centered at 5007Å having peak flux of 1.0x10^{-15} erg sec^{-1} cm^{-2} $Å^{-1}$, and hence a total flux of 1.0x10^{-14} erg sec^{-1} cm^{-2}. Alternatively, an emission line can be modeled as a Gaussian function:

```
spectrum = gauss( 5007, 10) * unit(1.0e-15,flam)
```

which describes a Gaussian line profile with 10Å FWHM centered at 5007Å and a peak flux density 1.0 x10^{-15} erg sec^{-1} cm^{-2} $Å^{-1}$. The total flux in such a Gaussian spectrum will be 1.054(FWHM)(peak flux density) or 1.05 x10^{-14} erg sec^{-1} cm^{-2} for this example. Spectra can also be added, if more than one emission line is needed. For example:

```
spectrum = gauss(5007,10)*unit(1.e-18,flam) + gauss(5020,10)*
unit(2.e-18,flam)
```

where all the text is place on a single line.

The actual photometric calculations are performed using CALCPHOT. Assuming IRAF is running, the SYNPHOT package is loaded, and that GENWAVE was run as described above, we then run CALCPHOT. Typing **`epar calcphot`** brings up a fill-out form as shown below; values are typed in, and **`<return>`** is used to go to the next line. After entering the various parameters, we then type **`:go`** to start the calculation.

Here is an example of a CALCPHOT run for an LRF central wavelength of 5007Å, and a model Gaussian spectrum centered at 5010Å having a FWHM of 5Å and total flux of

1.05x10^{-13} erg sec^{-1} cm^{-2}:

```
sy>epar calcphot

Image Reduction and Analysis Facility
PACKAGE = synphot
TASK = calcphot

obsmode = wfpc2,3,lrf#5007,a2d7  Instrument observation mode
spectrum= gauss(5010,5)*unit(2.0e-14,flam)  Synthetic spectrum
form    =               counts  Form for output data
(vzero  =                     ) List of values for variable zero
(output =                 none) Output table name
(append =                   no) Append to existing table?
(result =                  0.) Result of synphot calculation
(wavetab=          wavelen.tab) Wavelength table name
(refdata=                     ) Reference data
(mode   =                    a)

:go

Mode = band(wfpc2,3,lrf#5007,a2d7)
   Pivot       Equiv Gaussian
 Wavelength         FWHM
   5007.47        64.40982    band(wfpc2,3,lrf#5007,a2d7)
Spectrum:  gauss(5010,5)*unit(2.0e-14,flam)
    VZERO      (COUNTS s^-1 hstarea^-1)
       0.            4.52047
```

The results indicate that the target flux 1.05x10^{-13} erg sec^{-1} cm^{-2} will produce 4.5 DN s^{-1}. This can then be scaled to the actual countrate in the observed image, to obtain the target flux.

More complex spectra may require more characters than the fill-out form allows. In such cases the spectrum can be specified in a text file, and the name of the text file (proceeded by “@”) is given for the spectrum in CALCPHOT. For example, the following spectrum could be entered into a text file called `spectrum.dat` with any editor:

```
gauss(5007,15)*unit(1.e-16,flam)+gauss(5028,8)*unit(2.e-16,flam)
```

and then CALCPHOT is run on this spectrum:

```
sy>epar calcphot

Image Reduction and Analysis Facility
PACKAGE = synphot
TASK = calcphot

obsmode = wfpc2,3,lrf#5007,a2d7  Instrument observation mode
```

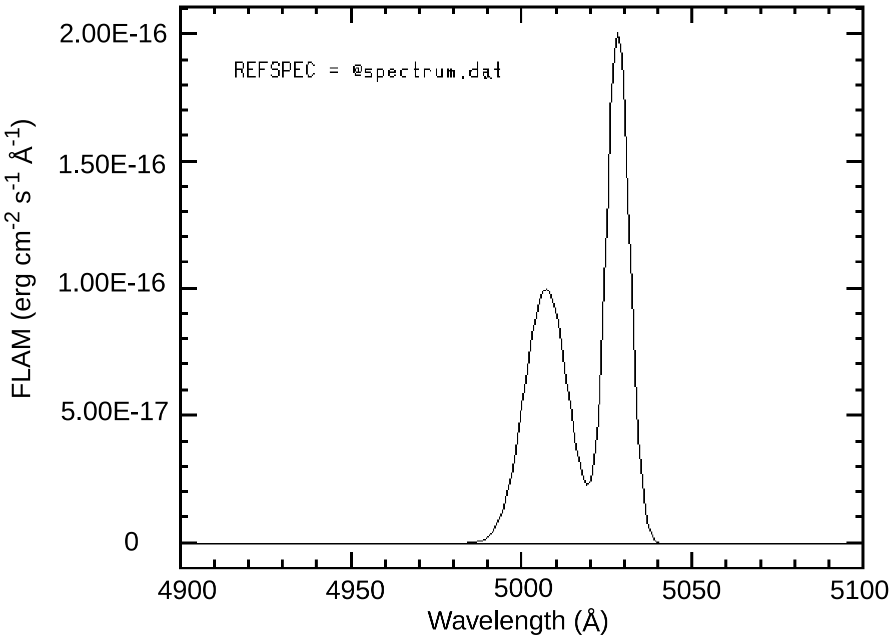
```
spectrum=        @spectrum.dat  Synthetic spectrum to calculate
form    =              counts  Form for output data
(vzero  =                    ) List of values for variable zero
(output =                none) Output table name
(append =                  no) Append to existing table?
(result =                  0.) Result of synphot calculation
(wavetab=         wavelen.tab) Wavelength table name
(refdata=                    ) Reference data
(mode   =                   a)

:go

Mode = band(wfpc2,3,lrf#5007,a2d7)
   Pivot       Equiv Gaussian
 Wavelength         FWHM
   5007.47        64.40982    band(wfpc2,3,lrf#5007,a2d7)
Spectrum:  gauss(5007,15) * unit(1.0e-16,flam) + gauss(5028,8) *
unit(2.0e-16,flam)
    VZERO      (COUNTS s^-1 hstarea^-1)
       0.           0.117225
```

The results indicate that the model spectrum will produce 0.12 DN s^{-1}. The input spectrum can be plotted using the PLSPEC task. Here we plot the input spectrum alone by leaving the OBSMODE blank, and request that the plot be in units of F_λ or "**`flam`**" (i.e. erg sec^{-1} cm^{-2} $Å^{-1}$). The plot limits are set to 4900Å to 5100Å:

```
sy>epar plspec

Image Reduction and Analysis Facility
PACKAGE = synphot
TASK = plspec

obsmode =                       Observation mode or @list
spectrum=        @spectrum.dat  Synthetic spectrum or @list
form    =                flam  Form of output graph
(vzero  =                    ) List of values for variable zero
(spfile =                none) Spectrophotometry data
(pfile  =                none) Photometry data
(errtyp =                   n) n[one] p[oint] c[ont] b[in]...
(left   =               4900.) x value for left side of graph
(right  =               5100.) x value for right side
(bottom =               INDEF) y value for bottom
(top    =               INDEF) y value for top
(append =                  no) Append to existing plot?
(ltype  =               solid) Line type: clear,solid,dashed,...
(device =            stdgraph) Graphics device
(wavetab=         wavelen.tab) Wavelength table name
(refdata=                    ) Reference data
(mode   =                   a)


:go
```

The resulting model target spectrum is shown in Figure 1.

Figure 1. Example of PLSPEC output for emission lines.



6.2 Stellar spectra

Stellar spectra can be modeled using catalogs of either observed or synthetic spectra incorporated in SYNPHOT. Appendix B in the *SYNPHOT User's Guide* lists the available spectra. For example, if we needed a model for an M6 III star with V=16.6, we could use star #166 in the Bruzual-Perrson-Gunn-Stryker Spectral Atlas, which is listed in Table B.5 of the *User's Guide* as bpgs_166, and re-normalize it to V=16.6 as follows:

```
spectrum = rn(crgridbpgs$bpgs_166,band(v),16.6,vegamag)
```

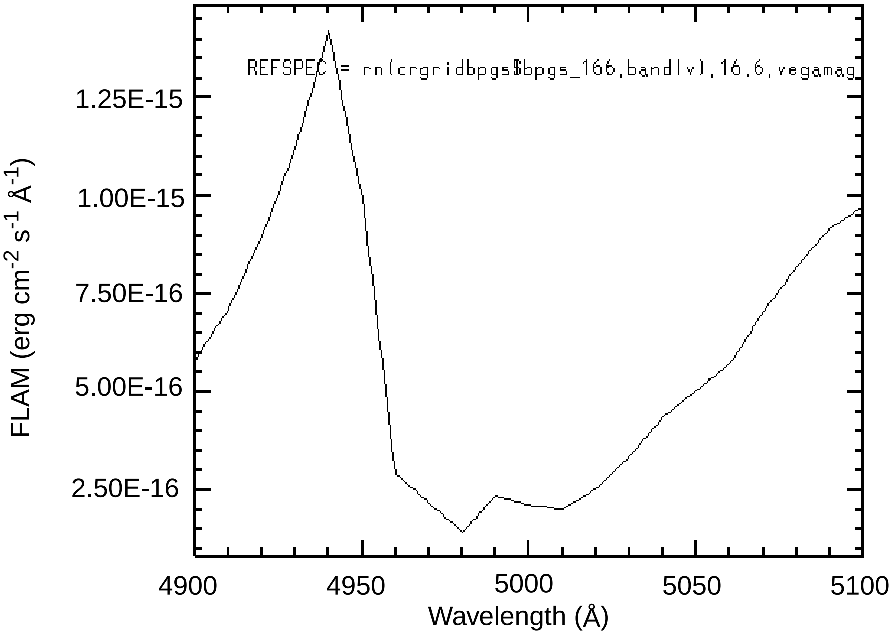
Using this as an input for CALCPHOT, we have:

```
sy>epar calcphot

Image Reduction and Analysis Facility
PACKAGE = synphot
TASK = calcphot

obsmode = wfpc2,3,lrf#5007,a2d7  Instrument observation mode
spectrum= rn(crgridbpgs$bpgs_166,band(v),16.6,vegamag)
```

```
form    =                 counts  Form for output data
(vzero  =                       ) List of values for variable zero
(output =                   none) Output table name
(append =                     no) Append to existing table?
(result =                     0.) Result of synphot calculation...
(wavetab=           wavelen.tab) Wavelength table name
(refdata=                       ) Reference data
(mode   =                      a)

:go

Mode = band(wfpc2,3,lrf#5007,a2d7)
   Pivot       Equiv Gaussian
 Wavelength         FWHM
   5007.47        64.40982    band(wfpc2,3,lrf#5007,a2d7)
Spectrum:  rn(crgridbpgs$bpgs_166,band(v),16.6,vegamag)
    VZERO      (COUNTS s^-1 hstarea^-1)
       0.           0.828713
```

Hence this star observed with the LRFs at a central wavelength of 5007Å results in 0.83 DN s^{-1}. The input spectrum may be plotted as above using PLSPEC, with the result shown in Figure 2.

Figure 2. Example of PLSPEC output for M6 III star.



6.3 Power law spectra

Power law spectra can be modeled using the `pl` function. For example,

```
spectrum = 2.3*pl(5500,0.7)
```

specifies a power law spectrum

$$f_\nu = 0.23\left(\frac{\lambda}{5500}\right)^{0.7} = 0.23\left(\frac{\nu}{5.45 \times 10^{14}}\right)^{-0.7}$$

where λ is in Å, and f_ν is in Janskys. This may also be re-written in terms of frequency ν in Hz, as shown. This can also be re-normalized to a standard magnitude:

```
spectrum = rn(pl(5500,0.7),band(v),16.3,vegamag)
```

where the power law is now specified to have V=16.3. These spectra can be used in CALCPHOT in the same manner as shown above for emission lines and stellar spectra, and similarly be plotted with PLSPEC.

In closing we recommend that LRF observers consult the WFPC2 LRF calibration web page (see references) for any developments and updates regarding LRF calibration.

7. References

Biretta, J. A., Ritchie, C. E., Baggett, S., and MacKenty, J. W. 1996a, “Wavelength / Aperture Calibration of the WFPC2 Linear Ramp Filters.” WFPC2 Instrument Science Report 96-05.

Biretta, J. A., et al., 1996b, *WFPC2 Instrument Handbook*, Version 4.0.

Bushouse, H., et al. 1992, “SYNPHOT User’s Guide.” 3rd ed.

Evans, R. 1992, “WFPC-2 Ramp Filter Predictors” JPL Interoffice Memorandum DM# 2031 (Dec. 30, 1992).

WWW page: `http://www.stsci.edu/ftp/instrument_news/WFPC2/wfpc2_top.html`

8. Appendix: Sample LRF + System Efficiency Curves

The curves below were generated in SYNPHOT using the following commands. Assuming the new SYNPHOT LRF table has been obtained and installed as described in Section 5, we start IRAF and load the SYNPHOT package. We then generate a finely stepped wavelength table with GENWAVE, and compute the throughput plots with PLBAND. Entering **`epar plband`** produces a fill-out form, which is completed as below by entering the parameters and then hitting **`<return>`**. After the fill-out form is completed, typing **`:go`** will run PLBAND and produce a plot on the screen. Text shown in **`boldface`** is entered by the user:

```
cl

stsdas

hst_calib

synphot

genwave wavelen.tab 1000. 12000. 1.

epar plband


Image Reduction and Analysis Facility
PACKAGE = synphot
TASK = plband

obsmode =     wfpc2,3,lrf#5000  Instrument mode or @list
(left   =                4900.) x value for left side of plot
(right  =                5100.) x value for right side of plot
(bottom =                INDEF) y value for bottom of plot
(top    =                INDEF) y value for top of plot
(normali=                   no) Normalization all curves to 1?
(ylog   =                   no) Take log of y values?
(append =                   no) Append to existing plot?
(ltype  =                solid) Line type: clear,solid,dashed,dotted,...
(device =             stdgraph) Graphics device
(wavetab=          wavelen.tab) Wavelength table name
(refdata=                     ) Reference data
(mode   =                    a)

:go
```

In this example the central wavelength has been set to 5000Å (i.e. the central wavelength specified on the Phase II proposal), and the plot runs from 4900Å to 5100Å. A hard copy can be generated by entering **`device=stdplot`**, and then typing **`gflush`** after PLBAND is done. Here the OTA+WFPC2 optics and CCD are included in the calculation; to plot the transmission of the LRF in isolation, omit "**`wfpc2,3`**" from the OBSMODE.

The plots in Figures A.1. through A.11. give the total efficiency for the OTA+WFPC2 optics, LRF, and CCDs together at central wavelengths from 3710Å to 9762Å with steps of 100Å between plots. Finer 50Å steps are used at the ends of the range.

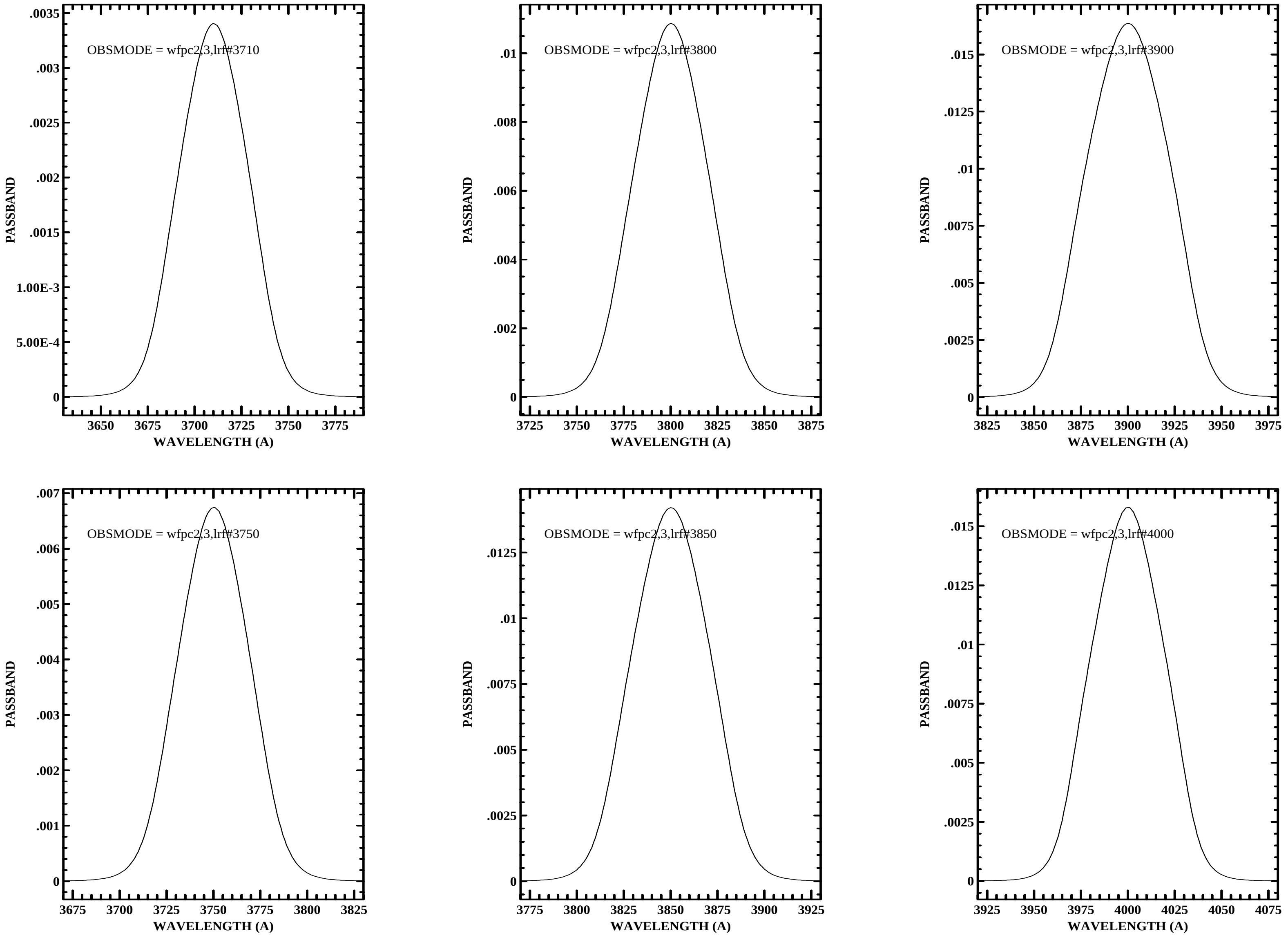


Figure A.1. LRF + System Efficiency for 3710Å through 4000Å.

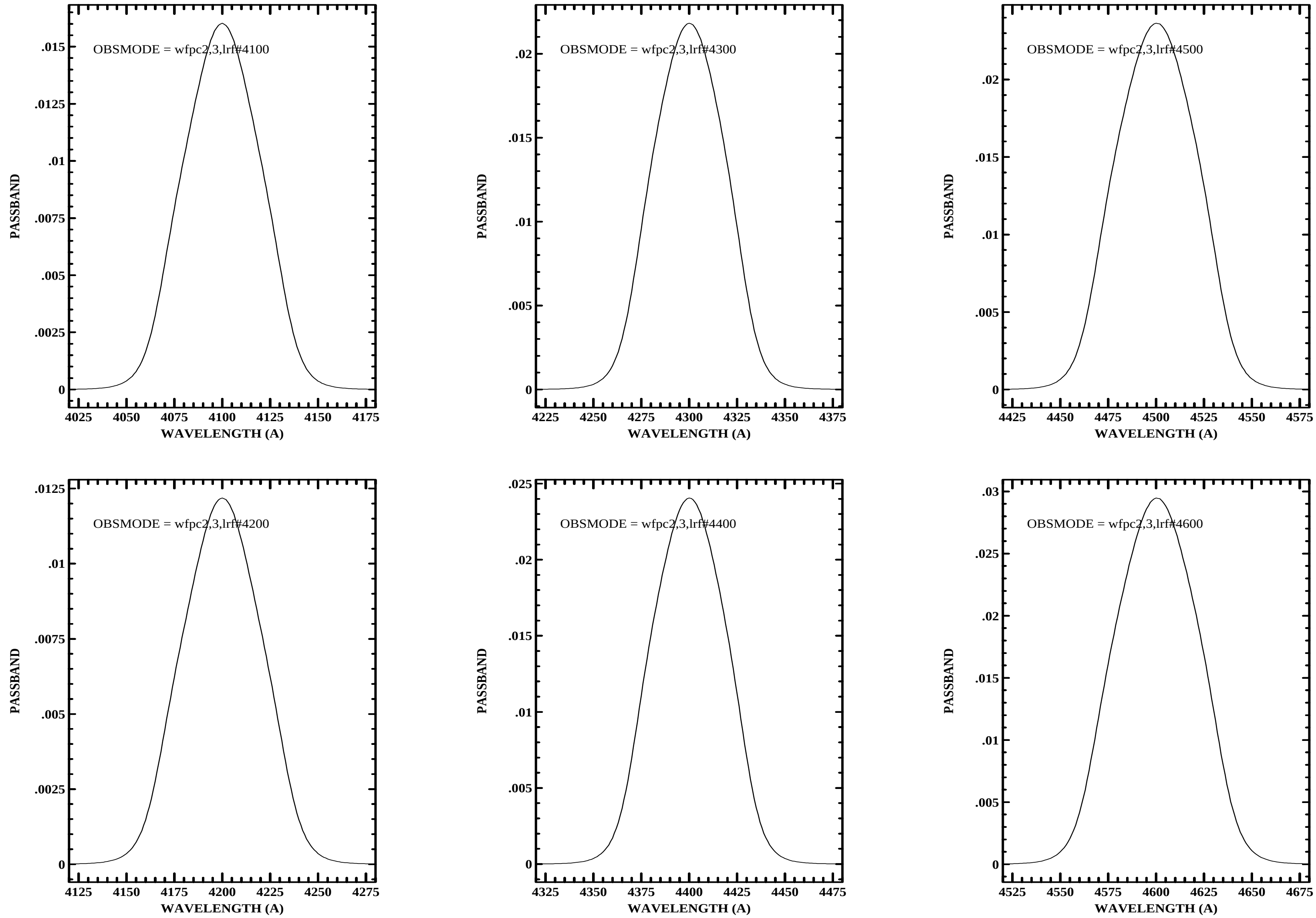


Figure A.2. LRF + System Efficiency for 4100Å through 4600Å.

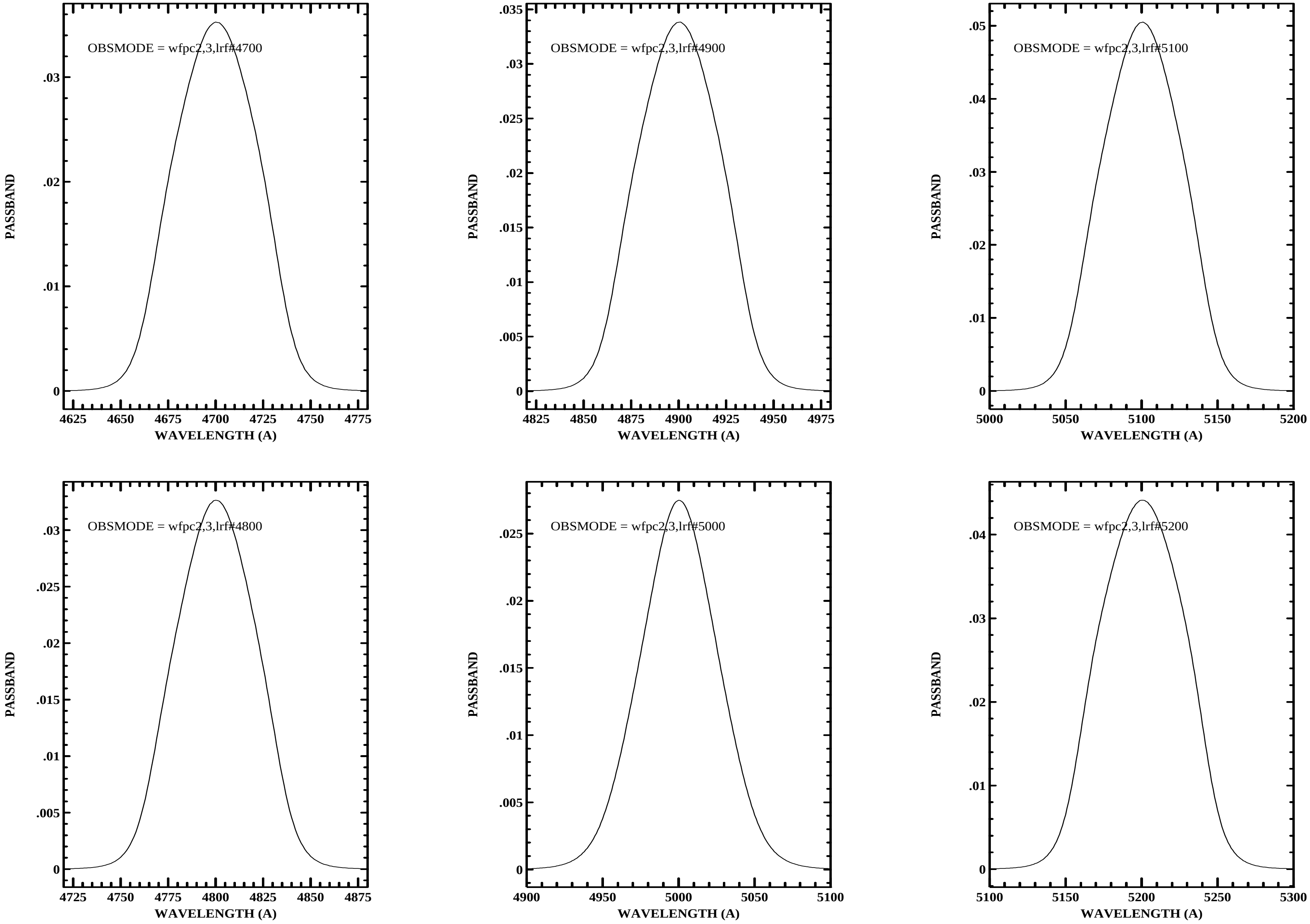


Figure A.3. LRF + System Efficiency for 4700Å through 5200Å.

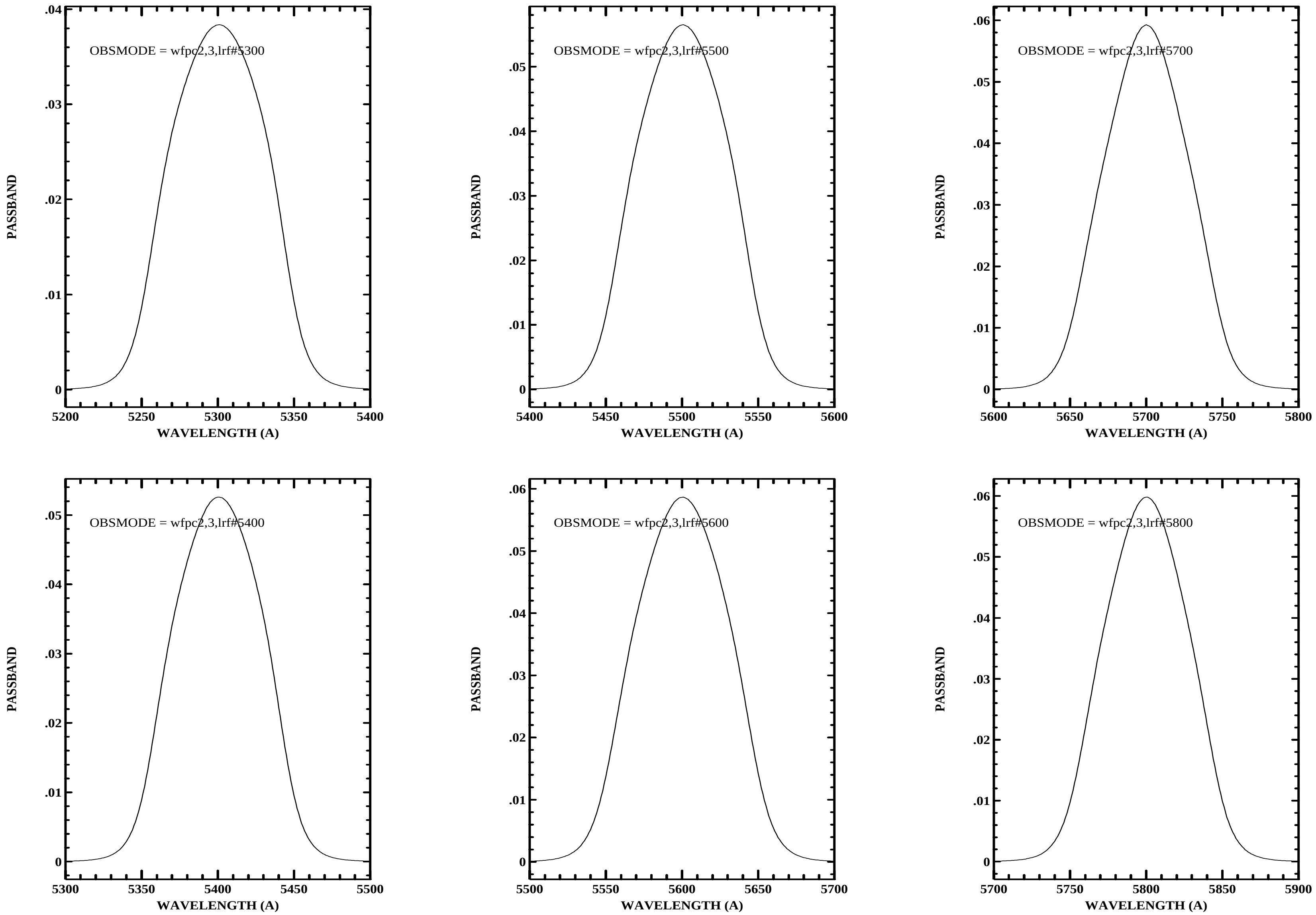


Figure A.4. LRF + System Efficiency for 5300Å through 5800Å

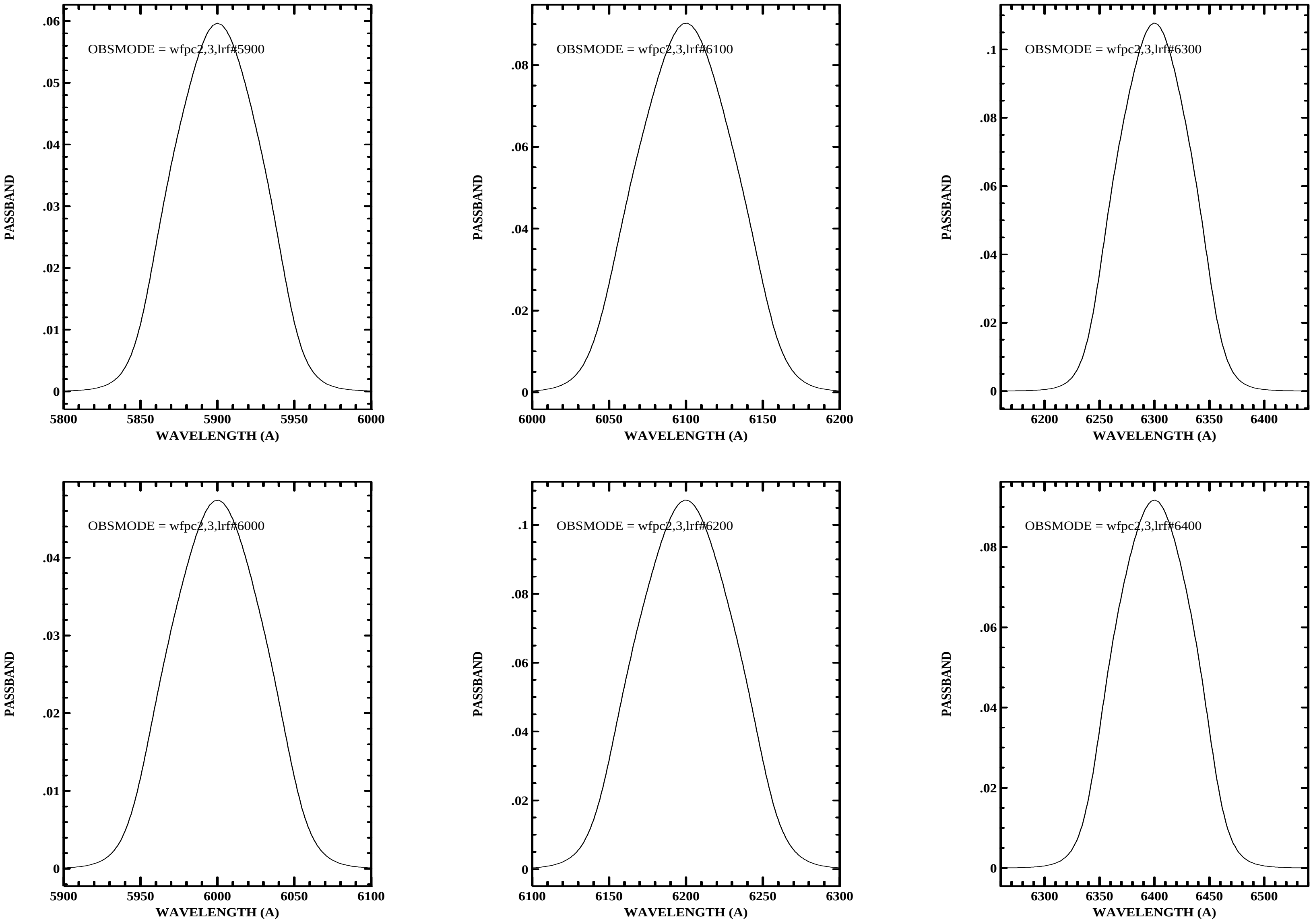


Figure A.5. LRF + System Efficiency for 5900Å through 6400Å.

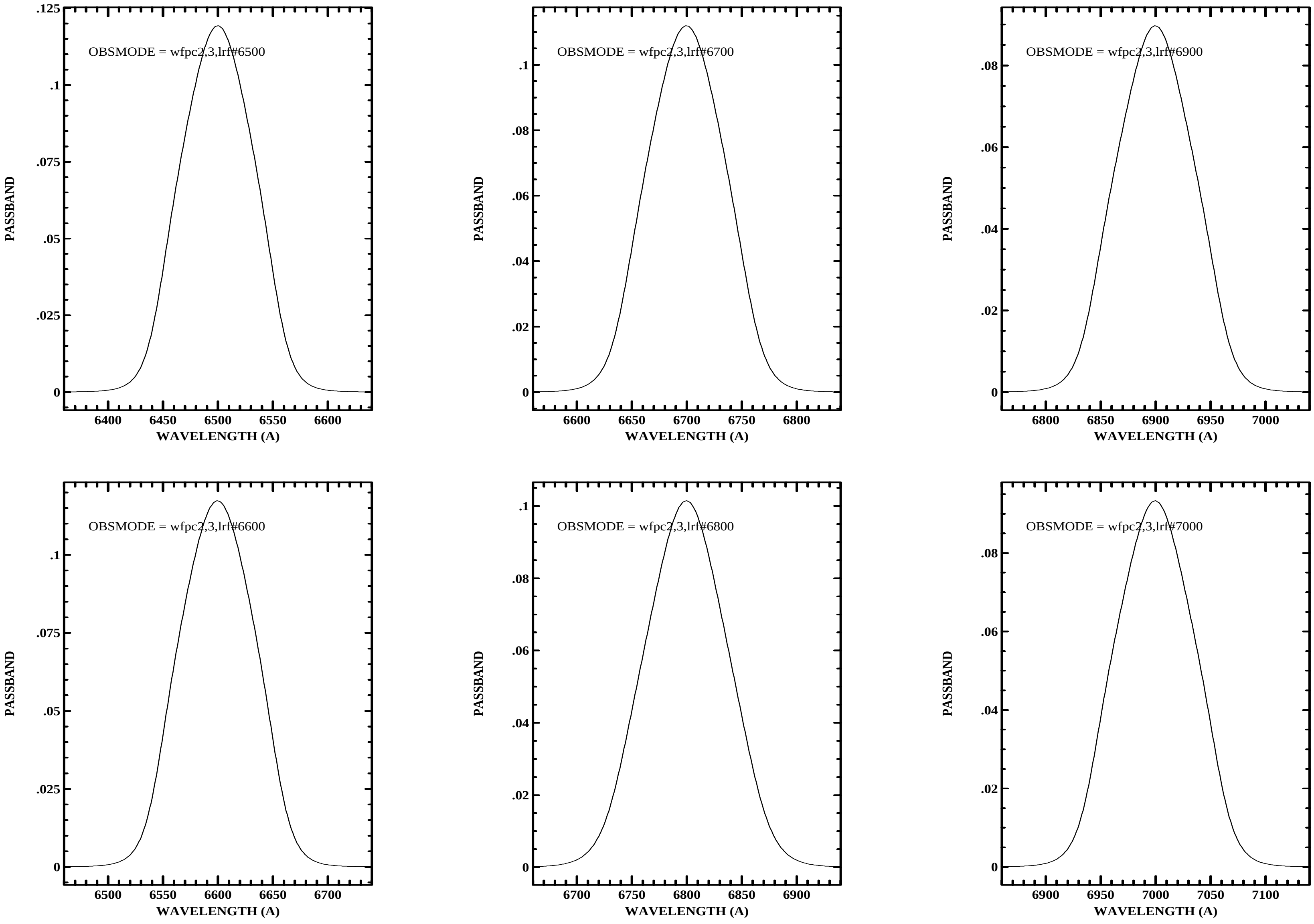


Figure A.6. LRF + System Efficiency for 6500Å through 7000Å.

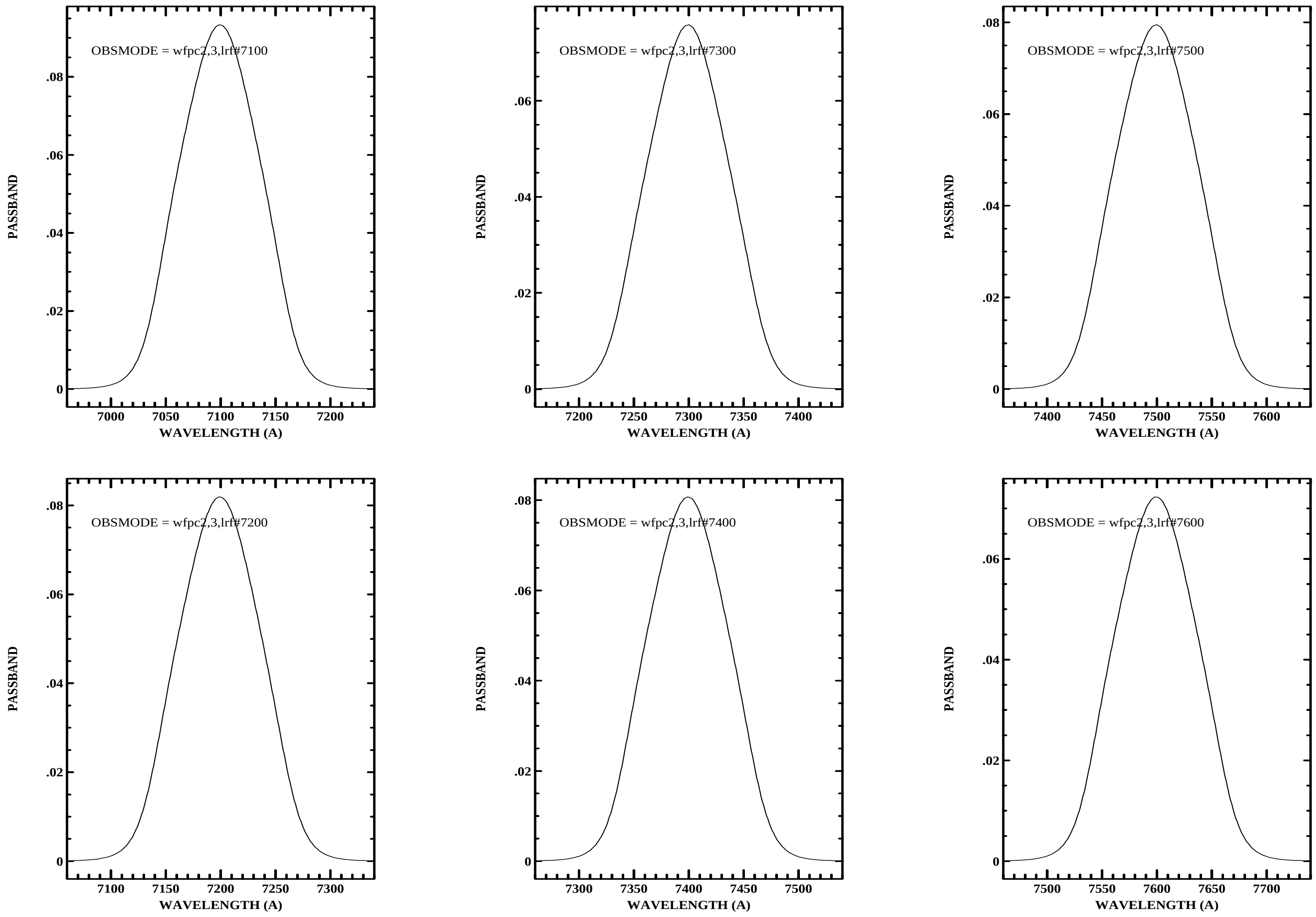


Figure A.7. LRF + System Efficiency for 7100Å through 7600Å.

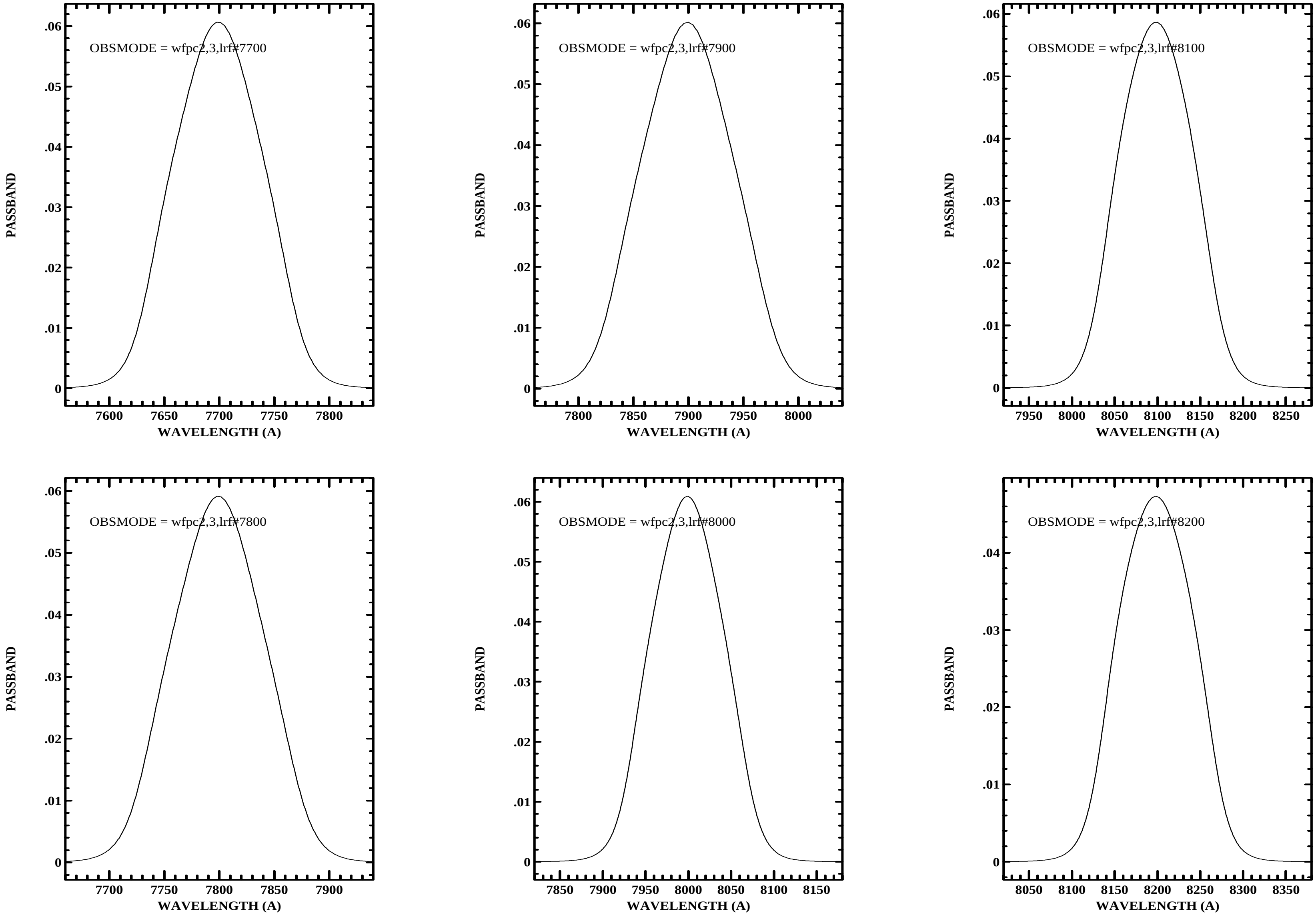


Figure A.8. LRF + System Efficiency for 7700Å through 8200Å.

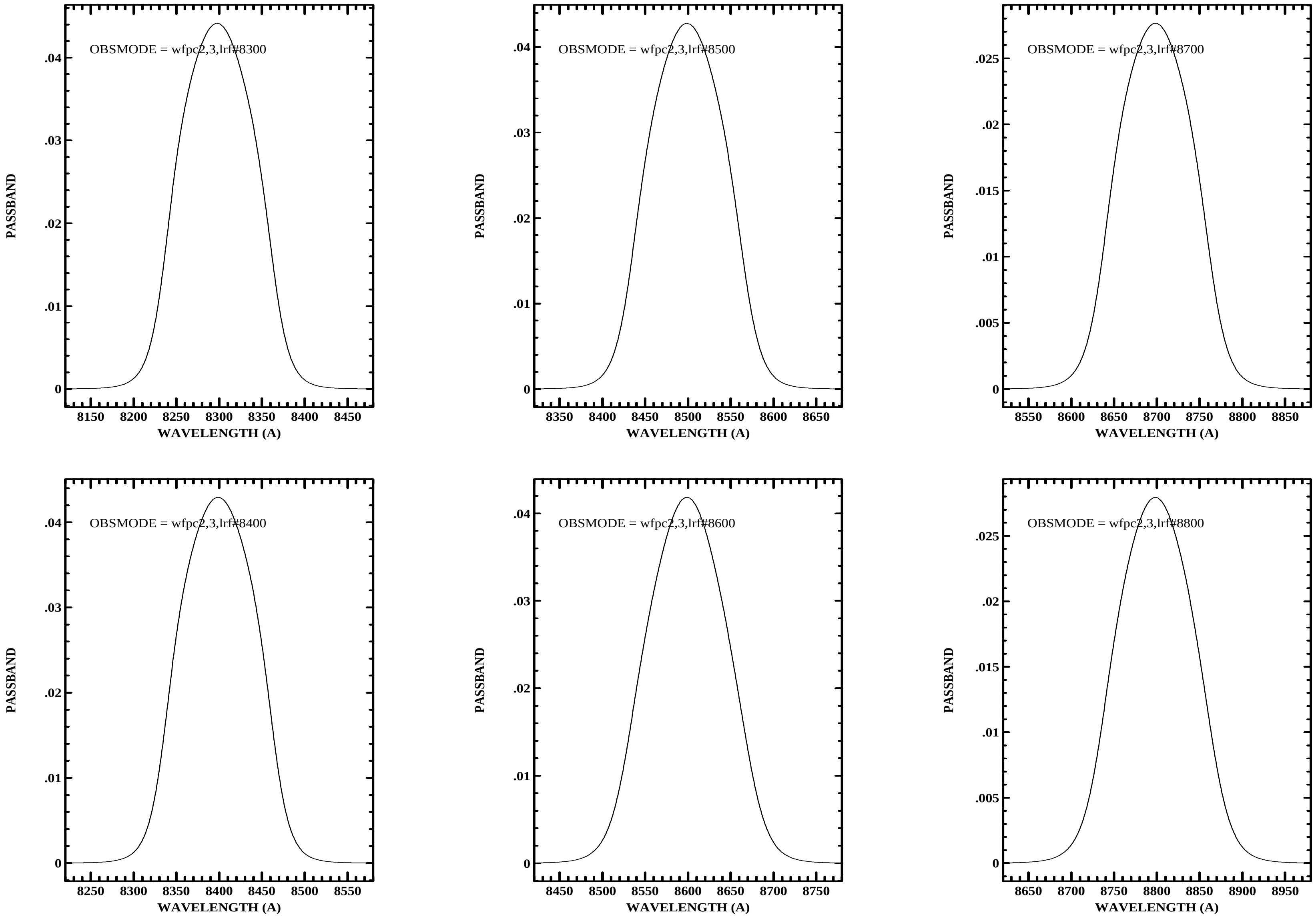


Figure A.9. LRF + System Efficiency for 8300Å through 8800Å.

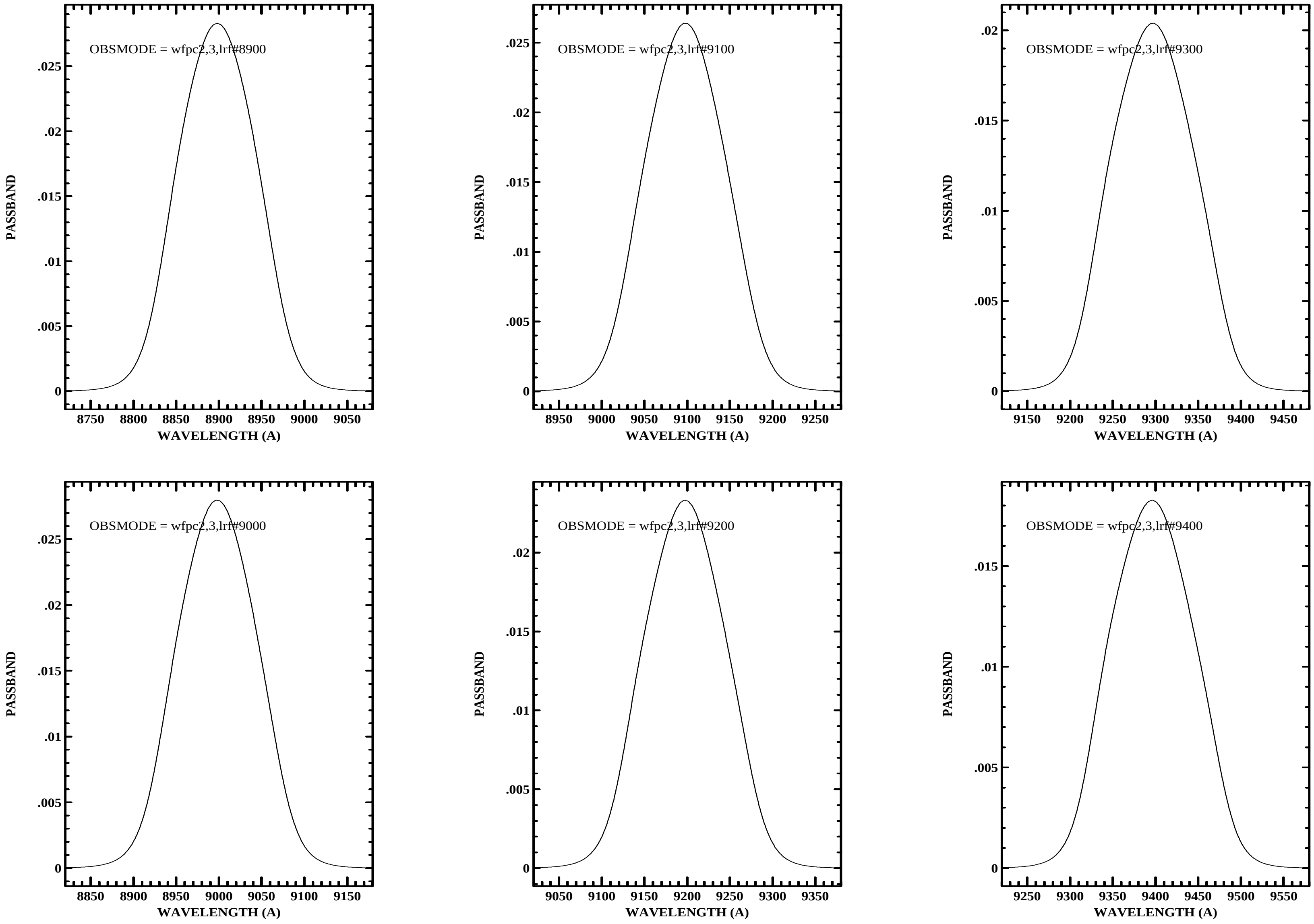


Figure A.10. LRF + System Efficiency for 8900Å through 9400Å.

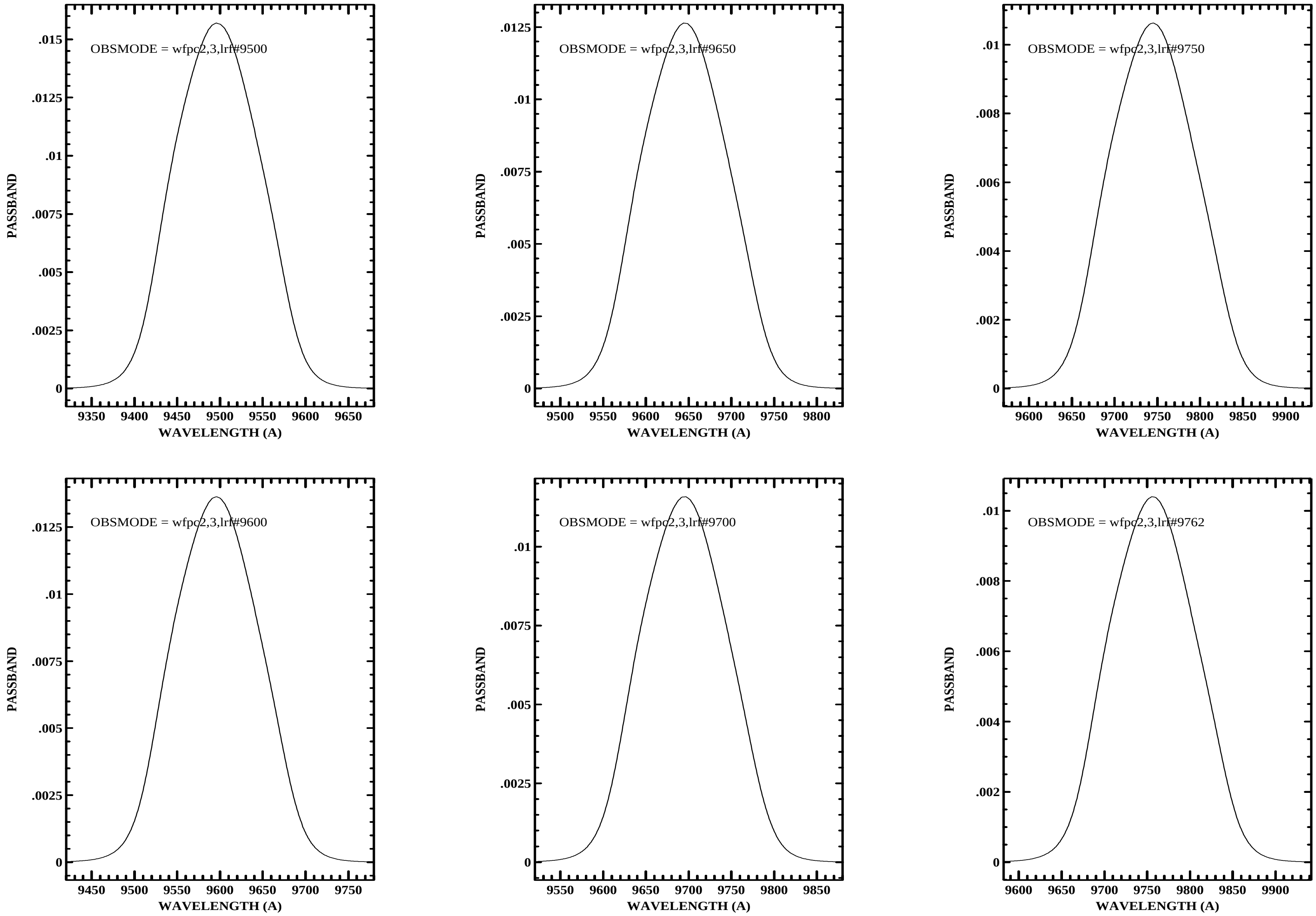


Figure A.11. LRF + System Efficiency for 9500Å through 9762Å.