ADVANCED WIDE-FIELD BROAD-PASSBAND REFRACTING FIELD CORRECTORS FOR LARGE TELESCOPES

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ABSTRACT

A preliminary 30-arcmin prime focus (f/2.0) refracting field corrector system for the University of California Ten-Meter Telescope (UC TMT) is presented which features 1/4-arcsec images containing more than 80% of the energy, over limited passbands within the wavelength range λ3300Å to λ1.0μ. Provision has been made in this system for an atmospheric dispersion corrector (ADC) but same has not yet been realized. Optical elements herein are small enough that this design could be scaled up to a Fifteen-Meter NNTT/SMT.

A compact 40-arcmin internal Cassegrain (f/1.75 hyperbola to f/5.0) broad-passband (λ3300Å to λ1.0μ) corrector, suitable for imaging and multi-object spectroscopy at the UC TMT, is presented which features 1/4-arcsec images containing more than 90% of the energy when averaged over field angle and color.

Three 60-arcmin external Cassegrain correctors for 300-inch f/1.8 and f/2.0 parabolic primary mirrors are presented which are suitable for a Fifteen-Meter NNTT/MMT. Image quality is comparable to the UC TMT Cassegrain corrector and it exceeds that of the UC TMT preliminary prime focus corrector system by a substantial margin. Each of these correctors contains an ADC which has been implemented in one example, eliminating 4.0 arcsec of differential atmospheric refraction with an rms residual of +/-0.10 arcsec over the broad passband (λ3300Å to λ1.0μ). A 60-arcmin external Cassegrain (f/1.8 extreme hyperbola to f/4.5) corrector with ADC yields yet a factor two in image quality but said hyperbolic primary mirror would be incompatible with angular field requirements in the thermal infrared.

A (300-inch) 40-arcmin external Cassegrain (f/1.0 parabola to f/4.0) broad-passband (λ3300Å to λ1.0μ) corrector with ADC is presented. Image quality is comparable to the previous Cassegrain correctors. The practicality of this design, together with recent advances in optical manufacturing capability of large, fast, nonspherical optics, suggests that relatively inexpensive compact telescopes of very large collecting area may be possible in the near future.

INTRODUCTION

Multiple-element refracting field correctors for wide-field, broad-passband imaging with single-mirror and two-mirror telescopes have been described in classical literature which is summarized and referenced in recent papers by Angel (1983), by Cao and Wilson (1983) and by Richardson et al. (1984). Notable among many substantive papers on this subject matter is the contribution by Faulde and Wilson (1973) wherein it is suggested that substantial improvement in image quality for a given field angle and chromatic passband can be obtained by the introduction of an aspheric surface within the field corrector.

The work documented herein represents the application of established principles to specific corrector designs under consideration for several large telescope projects. These correctors differ from those by previous authors in four aspects: 1) primary mirrors with faster f/ratios have been used; 2) Two mild aspheric surfaces have been used in each of the correctors; 3) Two plane-parallel plates of FK5 and LLF2 have been incorporated into each corrector to provide material for later design of a pair of counter-rotating zero-deviation prisms which will serve as an atmospheric dispersion corrector (ADC) unit in each corrector; 4) The optical design constraints on residual monochromatic aberration, and on axial as well as lateral color are considerably more severe than those achieved in the past.

The optimum telescope focal length for wide-field imaging depends upon the desired sampling factor at the focal plane (in pixels per arcsec) and also depends on the assumed pixel size (microns). The quantitative relationship is given by Table 1 shown below.

Table 1. OPTIMUM TELESCOPE FOCAL LENGTH (INCHES) FOR WIDE-FIELD IMAGING

		Pixel Size (microns)	
Sampling Factor	15	20	25
Poor seeing (4/arcsec)	487	650	812
Light (6/arcsec)	731	974	1218
Medium (8/arcsec)	974	1299	1624
Heavy (10/arcsec)	1218	1624	2030

The Gehrz Committee (1983) recommends a sampling factor ranging between 4 and 8 pixels per arcsec for the 15-meter NNTT. Faber (1983) (UC TMT Astronomy Advisory Council) favors approximately an 800-inch focal length for imaging on the UC TMT, while Angel (1983) recommends within the focal length range 1200 inches through 1800 inches for a 300-inch telescope. It thus appears that telescope focal lengths somewhere within the range 800 inches $<$ F.L. $<$ 2000 inches should be appropriate for properly sampled direct imaging provided detector pixel sizes in the future do not differ much from the presently available range of 15 to 25 microns.

Table 2 below illustrates that the best focal stations to achieve the desired focal length range for wide-field imaging depend on the primary mirror diameter. We exclude telescopes with primary mirrors slower than f/2.0 as being unnecessarily long and therefore too expensive to house for a given collecting area. The symbol "xxxxx" indicates that the corresponding focal length is not conveniently attainable in any reasonable optical design.

Table 2. BEST STATIONS TO ACHIEVE DESIRED FOCAL LENGTH (INCHES) FOR WIDE-FIELD IMAGING

	800 1200 1600 2000
300-inch Arizona Honeycomb	xxxxxxxxxxx f/4.0 .... f/6.0 ..... (External or Internal Cass)
400-inch UC TMT	f/2.0 xxxxxxxxxxxxxxxxxx ???? .....f/5.0 (Prime) (Internal Cass)
600-inch NNTT/SMT	Reimage ??? f/2.0 xxxxxxxxxxxxxxxxxxxxxxx (Prime)

Table 2 suggests that 300-inch telescopes with fast external or internal Cassegrain stations should be considered for imaging. A 400-inch telescope might be used at prime focus or internal Cassegrain but note that only the extremes of the desired focal length range are represented. A single-aperture 600-inch telescope may not be suitable at all for imaging if a prime focus corrector with ADC proves to be impossible to design or support mechanically. Table 2 was used as a guide in selecting telescope f/ratios and focal stations to be investigated in this paper.

DESIGN OBJECTIVES AND CONSTRAINTS

The optical design objectives and constraints selected for this study are outlined in Table 3 below, representing our collective opinion regarding reasonable and desirable standards of (theoretical geometric) performance to be expected from imaging optics for large telescopes of the future.

Table 3. DESIGN OBJECTIVES FOR WIDE-FIELD BROAD-PASSBAND CORRECTORS

A. GEOMETRIC RESTRICTIONS

1. 800 inches < focal length < 2000 inches.
2. 30 arcmin < angular field diameter < 60 arcmin.
3. Focal surface shall be flat.
4. Shroud obstruction < 20% area.
5. Element sizes, thicknesses and aspherics mechanically feasible and stable against (optical) bending.

B. MONOCHROMATIC RESTRICTIONS

1. Cassegrain optics usable near-axis in a "naked" two-mirror all-reflecting mode.
2. Primary mirror figure parabolic or mildly hyperbolic (compatible with thermal infrared field requirements).
3. Images to contain > 90% energy in 1/4 arcsec averaged over field angle and color (RMS diam < 0.16 arcsec if Gaussian).
4. Worst image to contain > 80% energy in 1/4 arcsec (RMS diam < 0.20 arcsec if Gaussian).
5. Distortion at full field < 1.0%.

C. COLOR-RELATED RESTRICTIONS

1. Accommodate chromatic passband from 3300Å thru 1.0μ (4.63 [F-C] units) at a single focus setting.
2. Provide an atmospheric dispersion corrector (ADC) and a flat 0.50-inch thick window near focus.
3. Maximum laterial color < 0.20 arcsec.
4. Average lateral color < +/-0.07 arcsec at worst field angle.

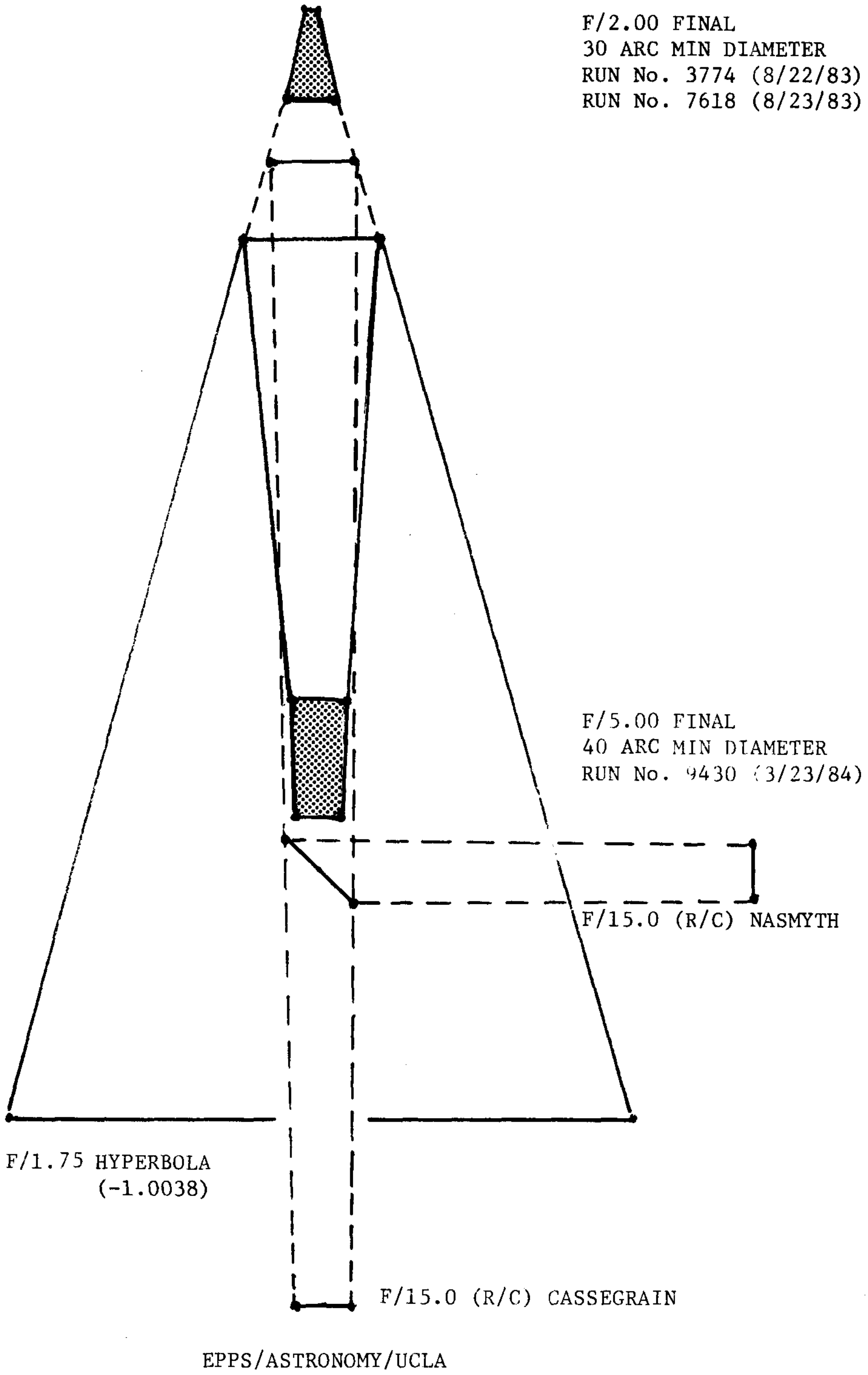
OPTICAL DESIGN DATA

Table 4 below outlines twenty (20) self-documenting figures which illustrate optical silhouettes, seven (7) quantitative corrector designs in full engineering detail and spot diagram analyses as a function of wavelength and field angle. The twenty (20) figures themselves follow Table 4 without interstitial discussion. A summary of field corrector geometry and optical performance data, a list of potential problem areas common to this generic class of broad-passband field correctors, and a summary of tentative conclusions follows the figures.

Table 4. OUTLINE OF OPTICAL DESIGN DATA FIGURES WHICH FOLLOW

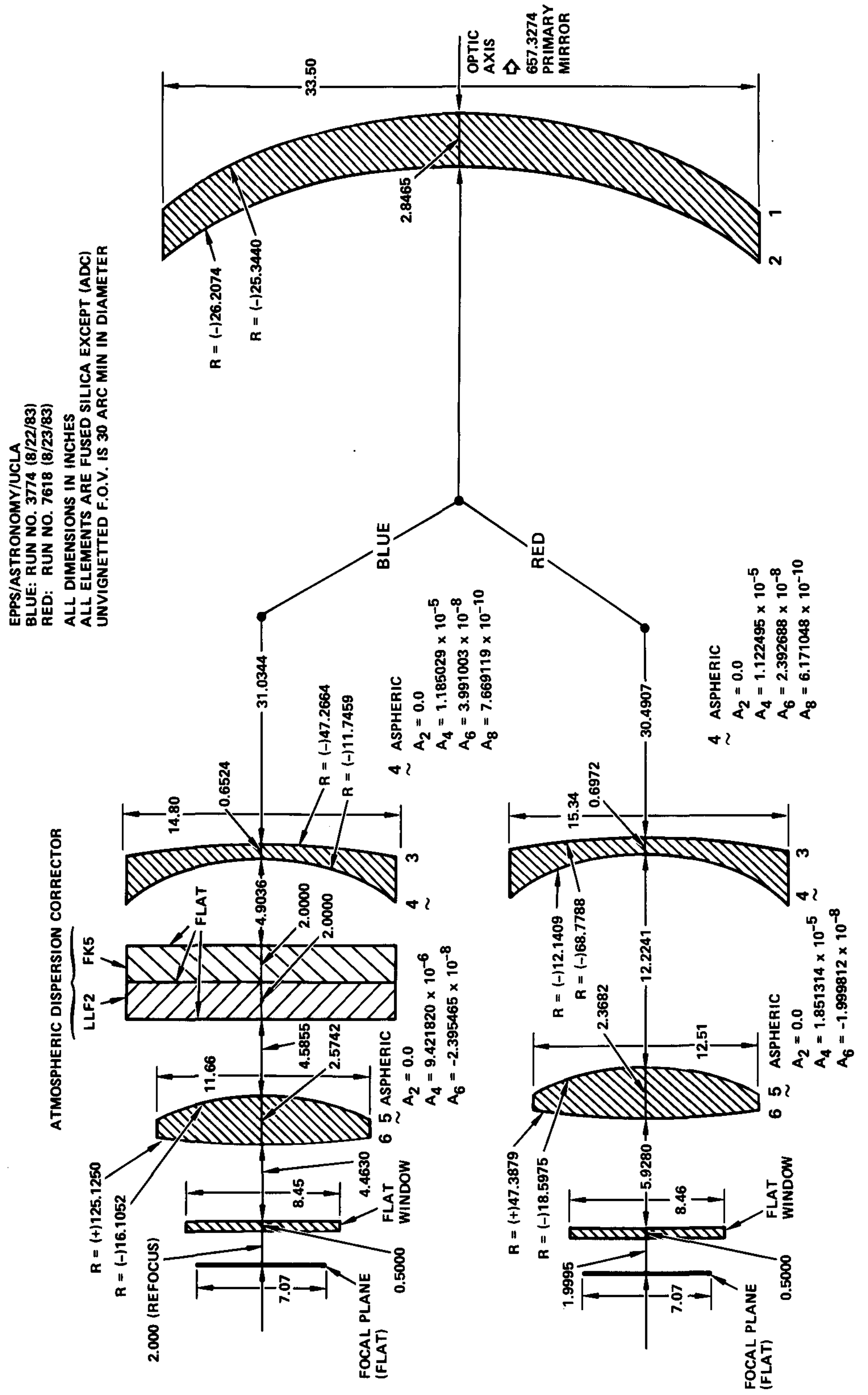
A. 400-INCH UC TMT (AND 600-INCH NNTT/SMT)
  1. Schematic UC TMT Telescope Geometry
  2. Prime Focus (f/2.0) Corrector System
  3. Mosaic of Spot Diagrams (UV) λ3300Å to λ4000Å (Blue Rear Section)
  4. Mosaic of Spot Diagrams (Blue J-Band) λ3900Å to λ5400Å (Blue Rear Section)
  5. Mosaic of (Unacceptable) Spot Diagrams (Visual) λ4400Å to λ7000Å Blue Rear Section)
  6. Mosaic of Spot Diagrams (Red) λ5000Å to λ1.0μ (Red Rear Section)
  7. Internal Cassegrain (f/1.5 Hyperbola to f/5.0) Corrector
  8. Mosaic of Spot Diagrams (Broad Passband) λ3300Å to λ1.0μ

B. 300-INCH ARIZONA HONEYCOMB (AND 600-INCH EQUIVALENT NNTT/MMT)
  9. Schematic Telescope Geometry (4-Corrector Study)
  10. External Cassegrain (f/2.0 Parabola to f/6.0) Corrector
  11. Mosaic of Spot Diagrams (Broad Passband) λ3300Å to λ1.0μ
  12. External Cassegrain (f/2.0 Parabola to f/5.0) Corrector
  13. Mosaic of Spot Diagrams (Broad Passband) λ3300Å to λ1.0μ
  14. External Cassegrain (f/1.8 Parabola to f/4.5) Corrector
  15. Mosaic of Spot Diagrams (Broad Passband) λ3300Å to λ1.0μ
  16. External Cassegrain (f/1.8 Extreme Hyperbola to f/4.5) Corrector
  17. Mosaic of Spot Diagrams (Broad Passband) λ3300Å to λ1.0μ
  18. Schematic Telescope Geometry (Fast Cassegrain)
  19. External Cassegrain (f/1.0 Parabola to f/4.0) Corrector
  20. Mosaic of Spot Diagrams (Broad Passband) λ3300Å to λ1.0μ



THREE-ELEMENT FIELD CORRECTORS (WITH WINDOW AND ADC) FOR THE UC TMT

Figure 1

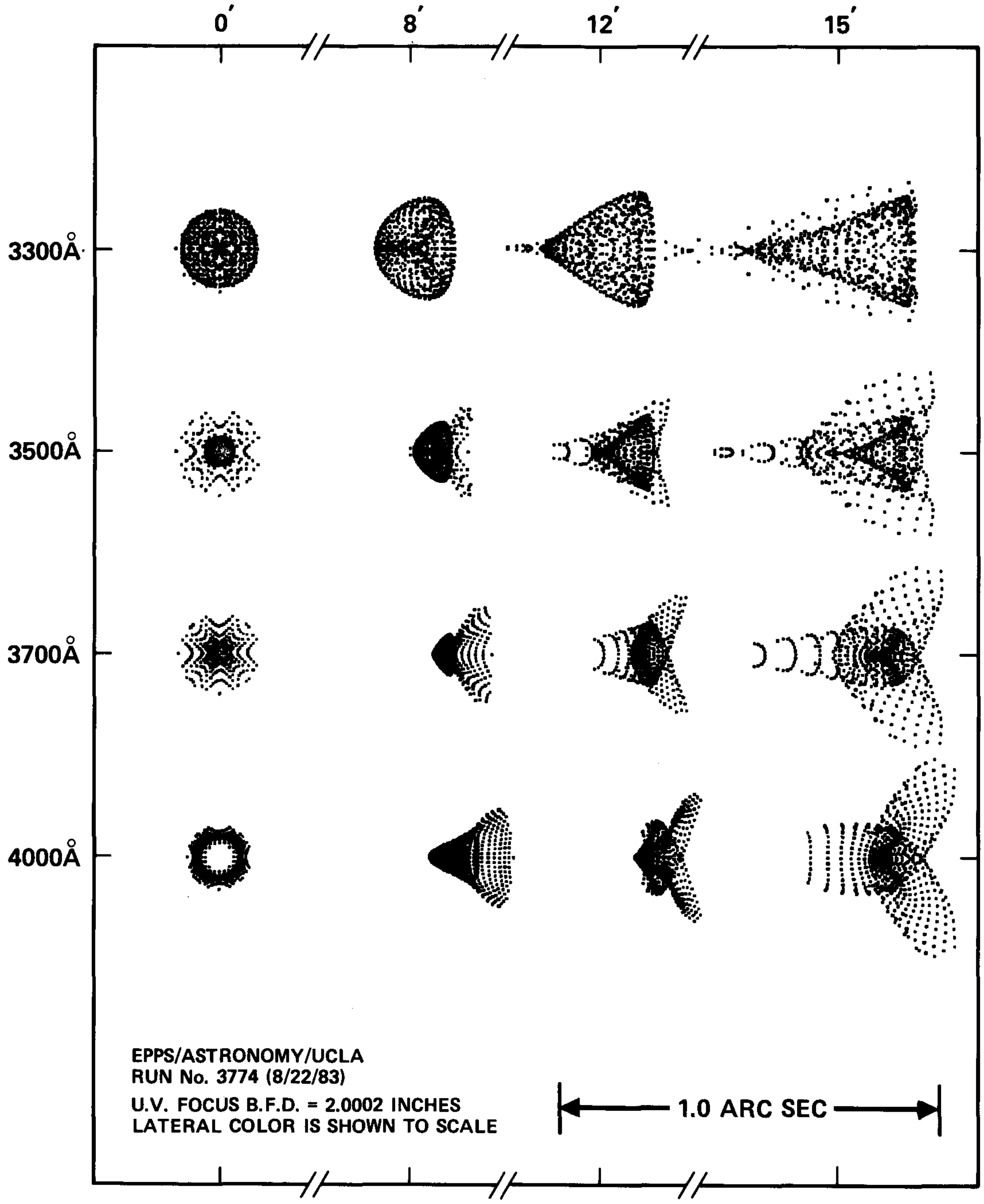

EPPS/ASTRONOMY/UCLA
BLUE: RUN NO. 3774 (8/22/83)
RED: RUN NO. 7618 (8/23/83)

ALL DIMENSIONS IN INCHES
ALL ELEMENTS ARE FUSED SILICA EXCEPT (ADC)
UNVIGNETTED F.O.V. IS 30 ARC MIN IN DIAMETER

THREE-ELEMENT *f*/2.00 CORRECTOR SYSTEM FOR UC TEN-METER (400-INCH) PRIMARY MIRROR

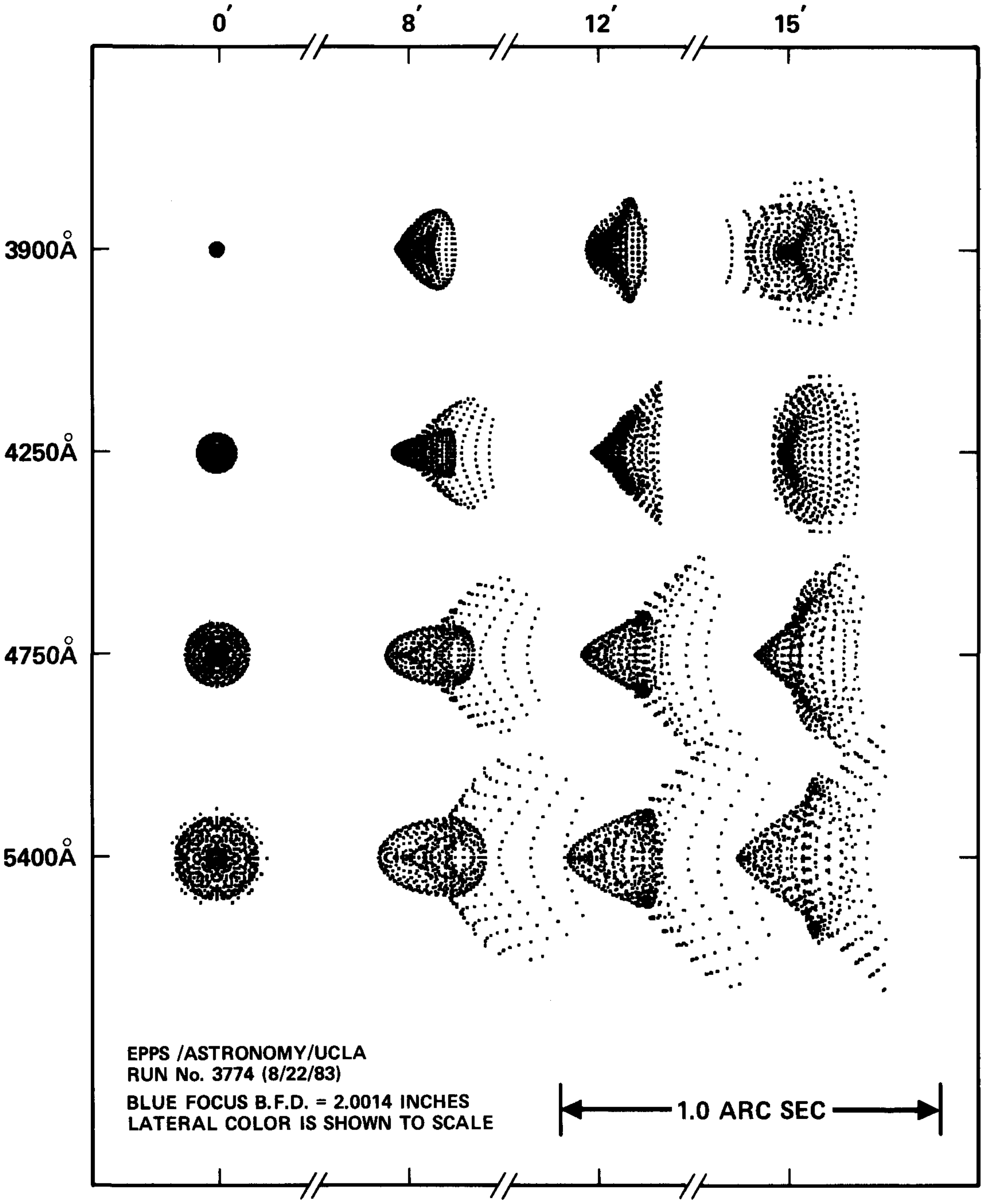
{ PRIMARY R = (-)1422.7271, A_2 = -1.0037963 }

Figure 2



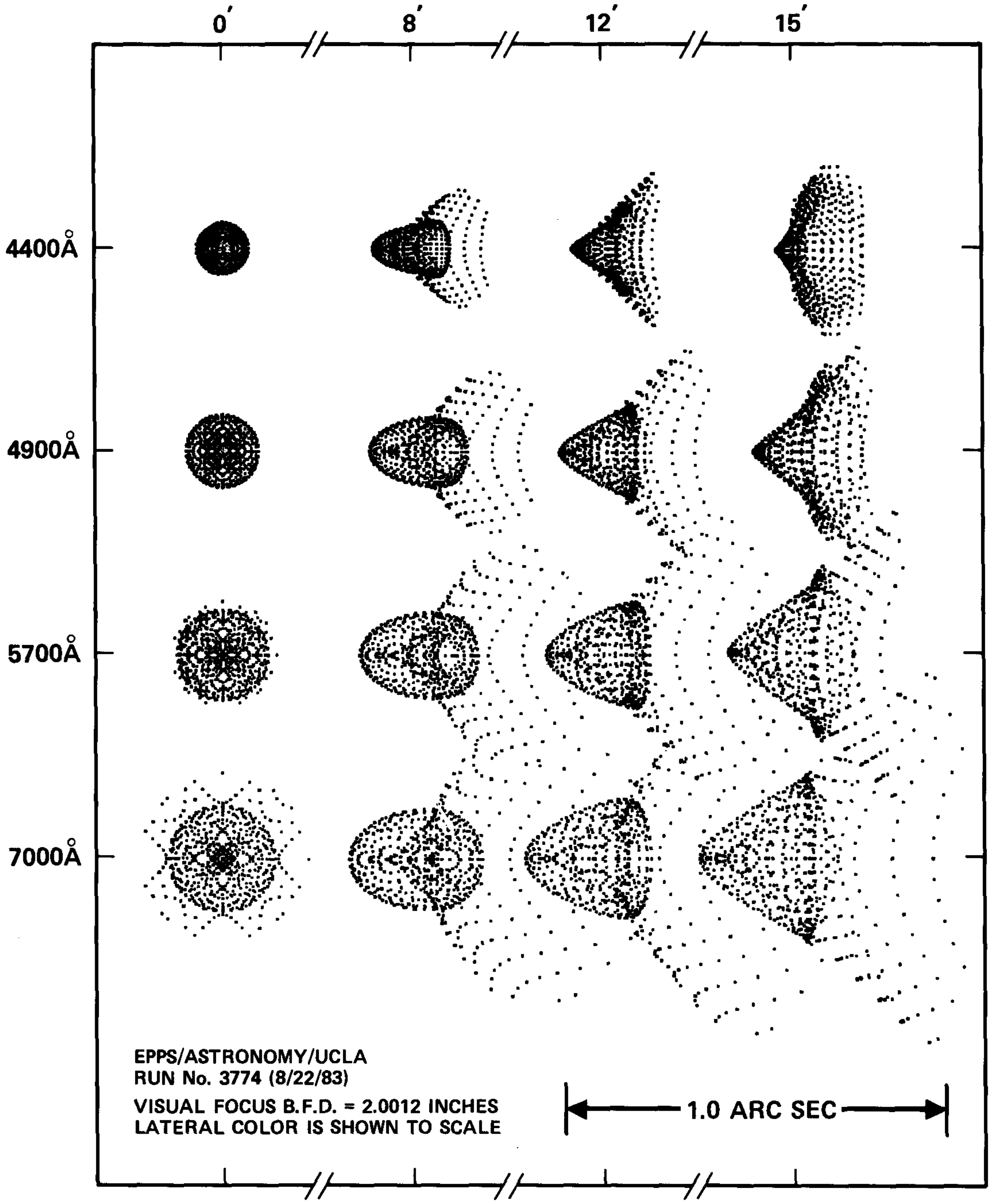
MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT *f*/2.00 PRIME FOCUS CORRECTOR SYSTEM
WITH AN *f*/1.78 HYPERBOLIC PRIMARY (A_2 = -1.0037963)

Figure 3



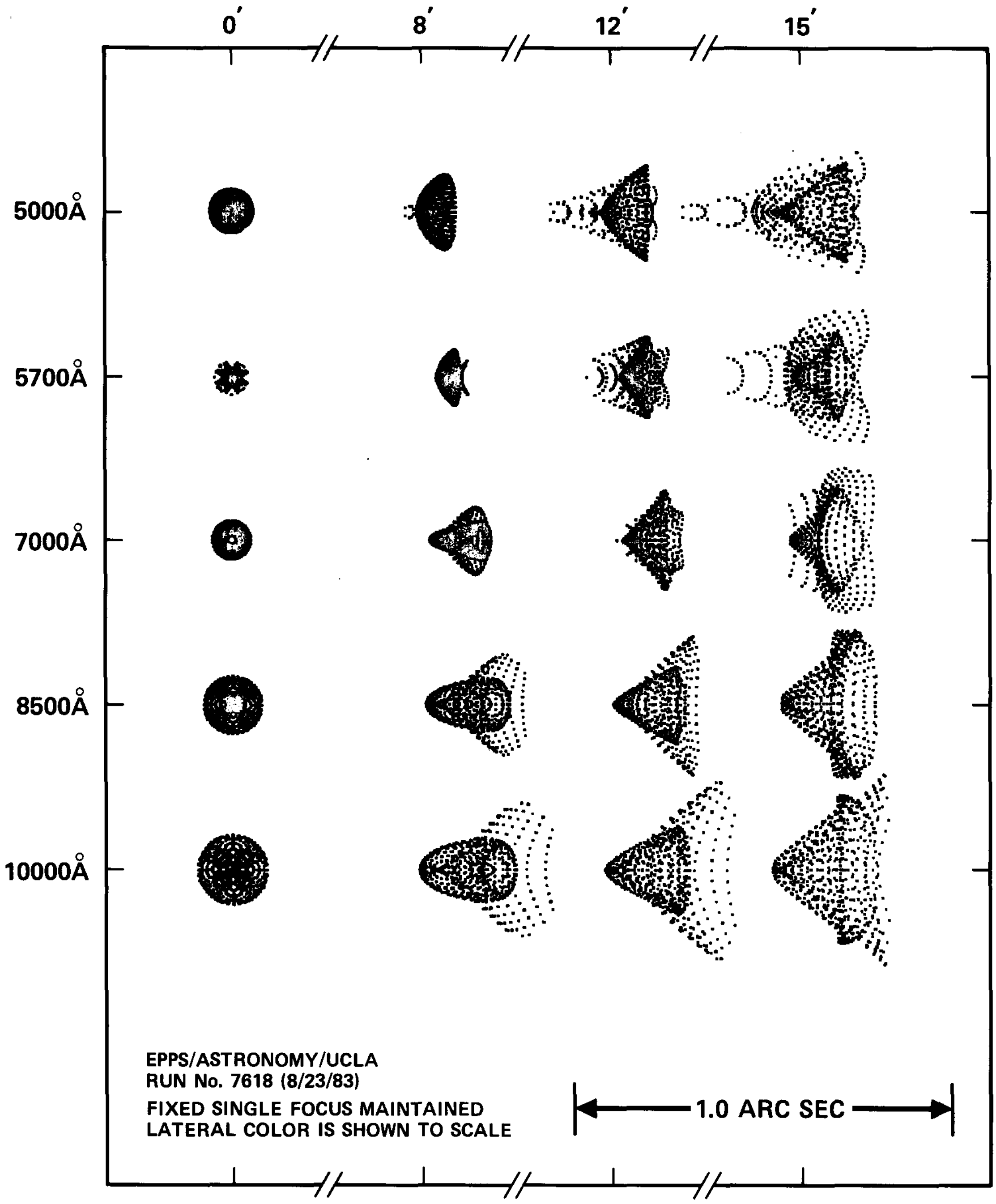
MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT *f*/2.00 PRIME FOCUS CORRECTOR SYSTEM
WITH AN *f*/1.78 HYPERBOLIC PRIMARY (A_2 = -1.0037963)

Figure 4



MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT *f*/2.00 PRIME FOCUS CORRECTOR SYSTEM
WITH AN *f*/1.78 HYPERBOLIC PRIMARY (A_2 = -1.0037963)

Figure 5



MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT $f/2.00$ PRIME FOCUS CORRECTOR SYSTEM
WITH AN $f/1.78$ HYPERBOLIC PRIMARY ($A_2 = -1.0037963$)

Figure 6

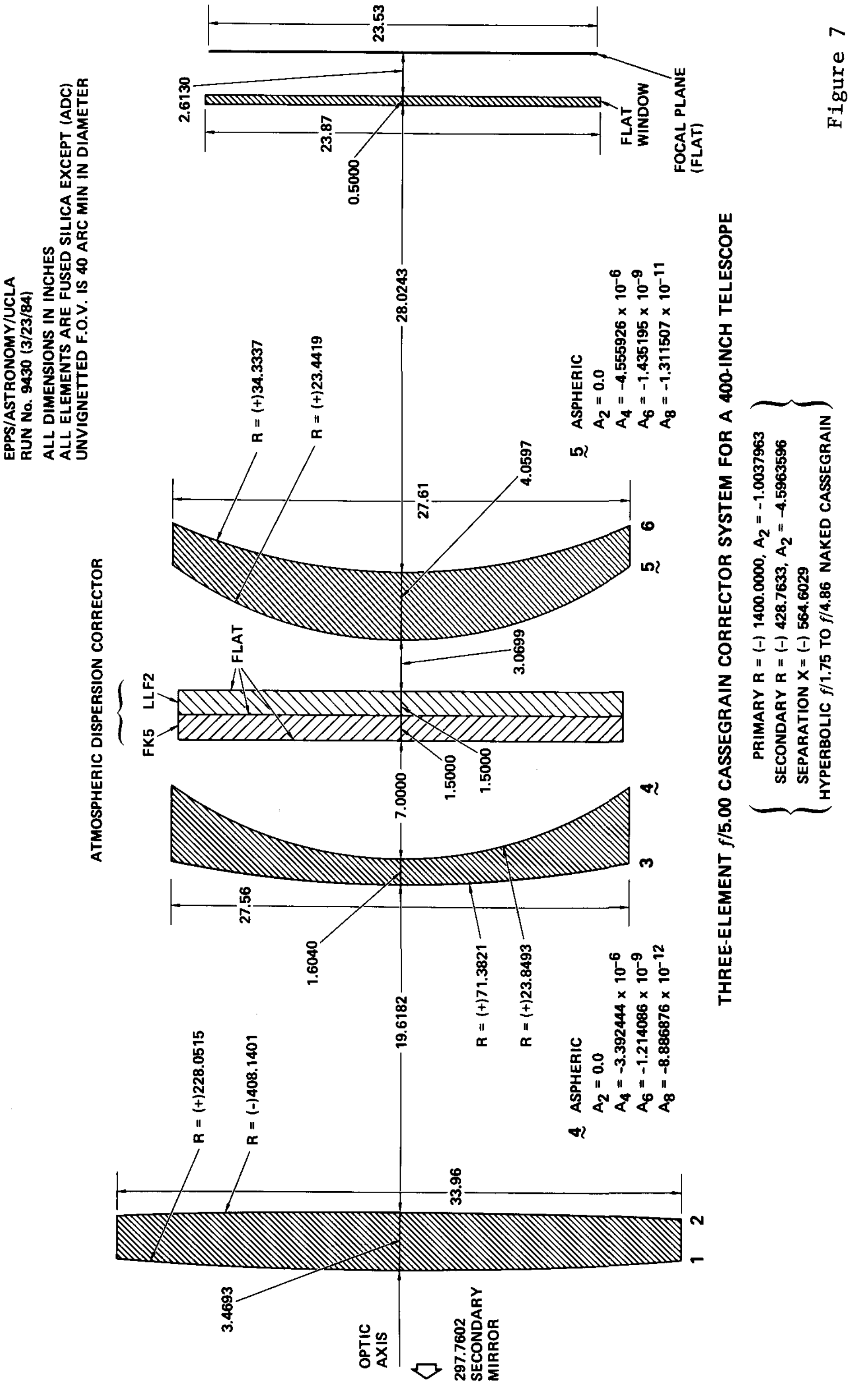
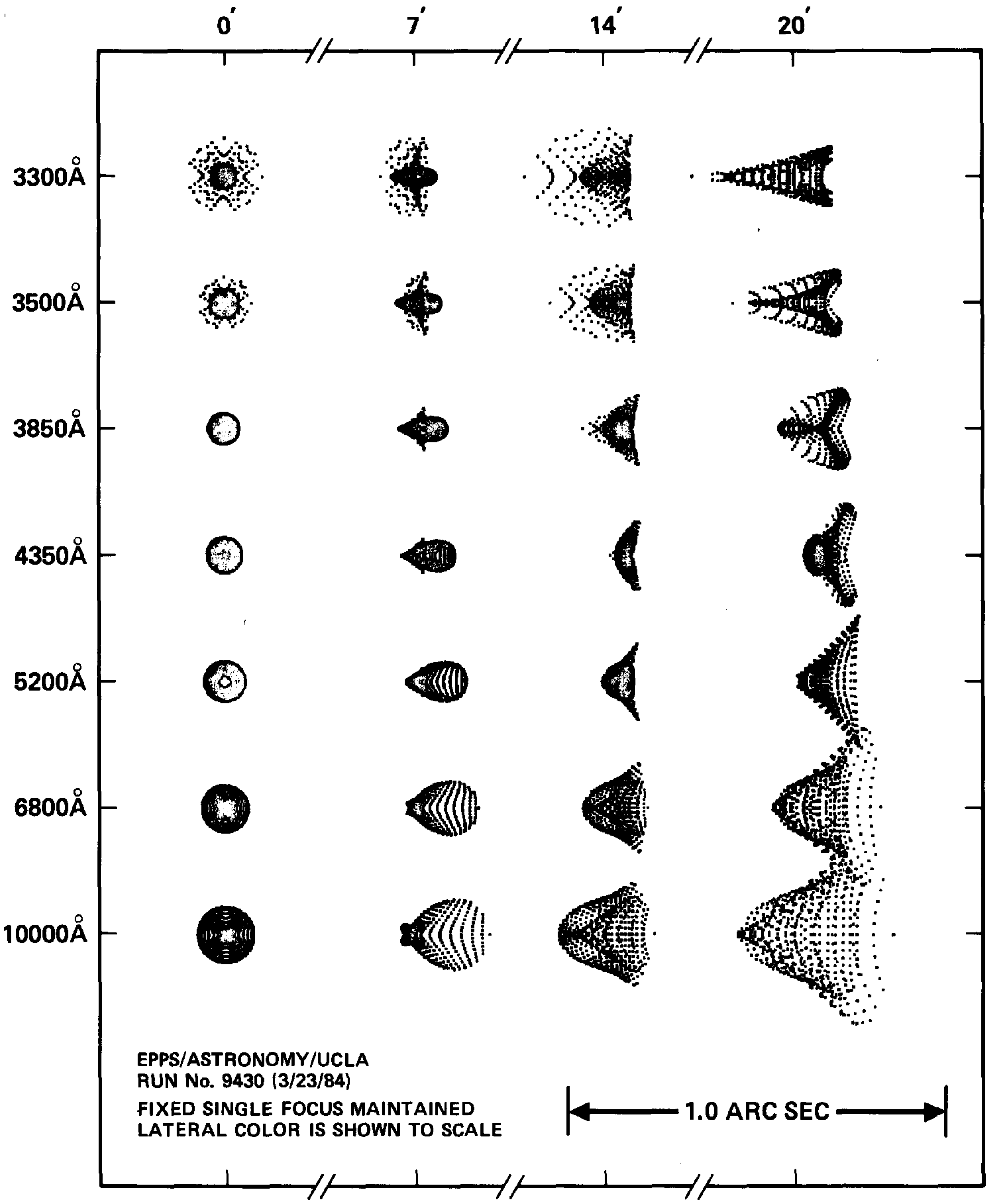

EPPS/ASTRONOMY/UCLA
RUN No. 9430 (3/23/84)
ALL DIMENSIONS IN INCHES
ALL ELEMENTS ARE FUSED SILICA EXCEPT (ADC)
UNVIGNETTED F.O.V. IS 40 ARC MIN IN DIAMETER
ATMOSPHERIC DISPERSION CORRECTOR
FK5
LLF2
FLAT
R = (+)228.0515
R = (-)408.1401
3.4693
33.96
19.6182
1.6040
27.56
R = (+)71.3821
R = (+)23.8493
7.0000
1.5000
1.5000
3.0699
R = (+)34.3337
R = (+)23.4419
27.61
4.0597
28.0243
0.5000
23.87
2.6130
23.53
FLAT WINDOW
FOCAL PLANE (FLAT)
OPTIC AXIS
297.7602 SECONDARY MIRROR
1
2
3
4
5
6
4 ASPHERIC
$A_2 = 0.0$
$A_4 = -3.392444 \times 10^{-6}$
$A_6 = -1.214086 \times 10^{-9}$
$A_8 = -8.886876 \times 10^{-12}$
5 ASPHERIC
$A_2 = 0.0$
$A_4 = -4.555926 \times 10^{-6}$
$A_6 = -1.435195 \times 10^{-9}$
$A_8 = -1.311507 \times 10^{-11}$
THREE-ELEMENT f/5.00 CASSEGRAIN CORRECTOR SYSTEM FOR A 400-INCH TELESCOPE
PRIMARY R = (-) 1400.0000, A_2 = -1.0037963
SECONDARY R = (-) 428.7633, A_2 = -4.5963596
SEPARATION X = (-) 564.6029
HYPERBOLIC f/1.75 TO f/4.86 NAKED CASSEGRAIN

Figure 7



MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT $f/5.00$ CASSEGRAIN CORRECTOR SYSTEM
WITH AN $f/1.75$ HYPERBOLIC PRIMARY ($A_2 = -1.0037963$)

Figure 8

THREE-ELEMENT BROAD PASSBAND 1.0 DEGREE FIELD CORRECTORS (WITH WINDOW AND ADC)

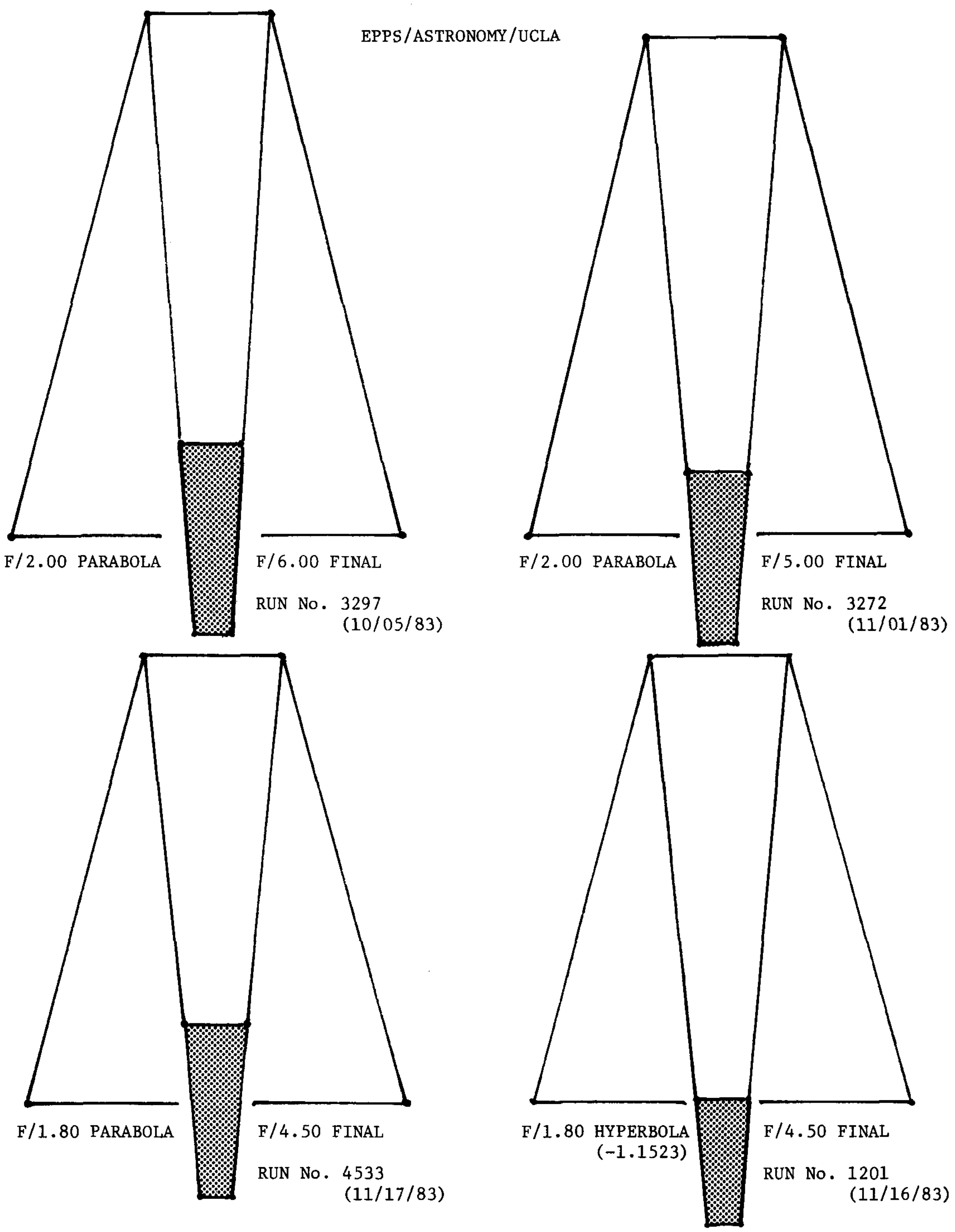
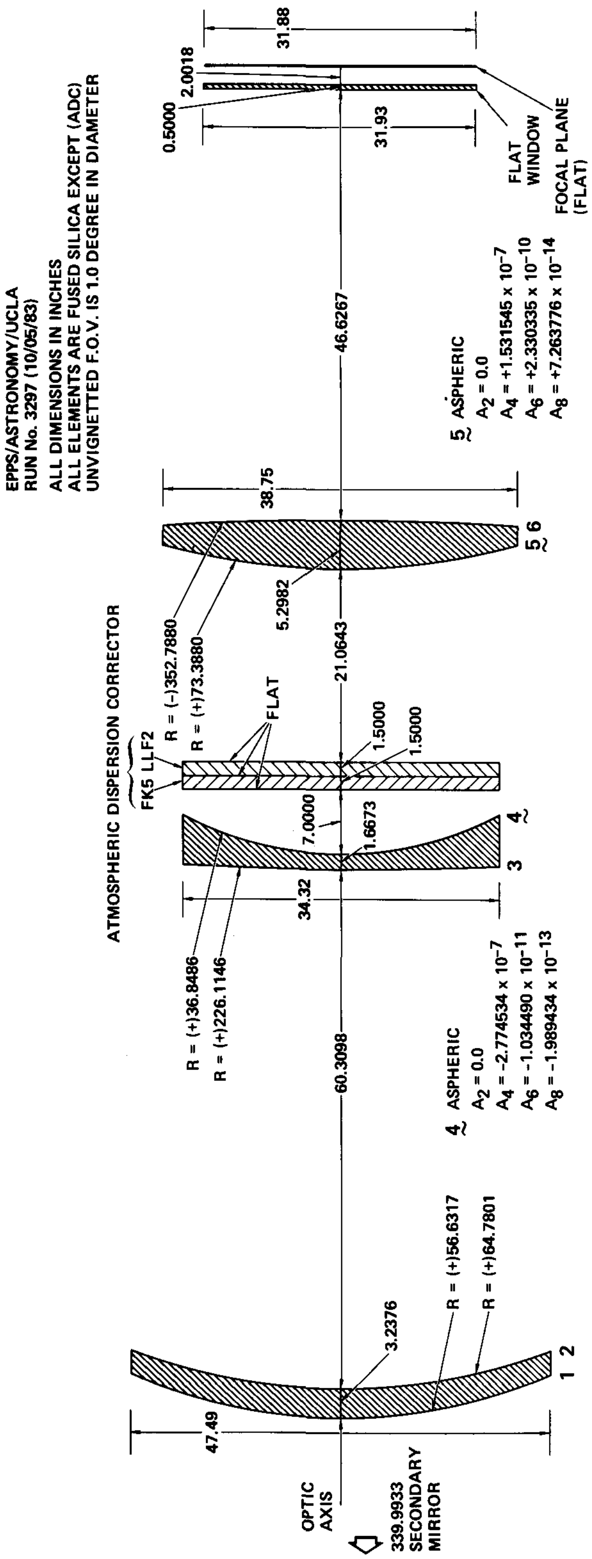


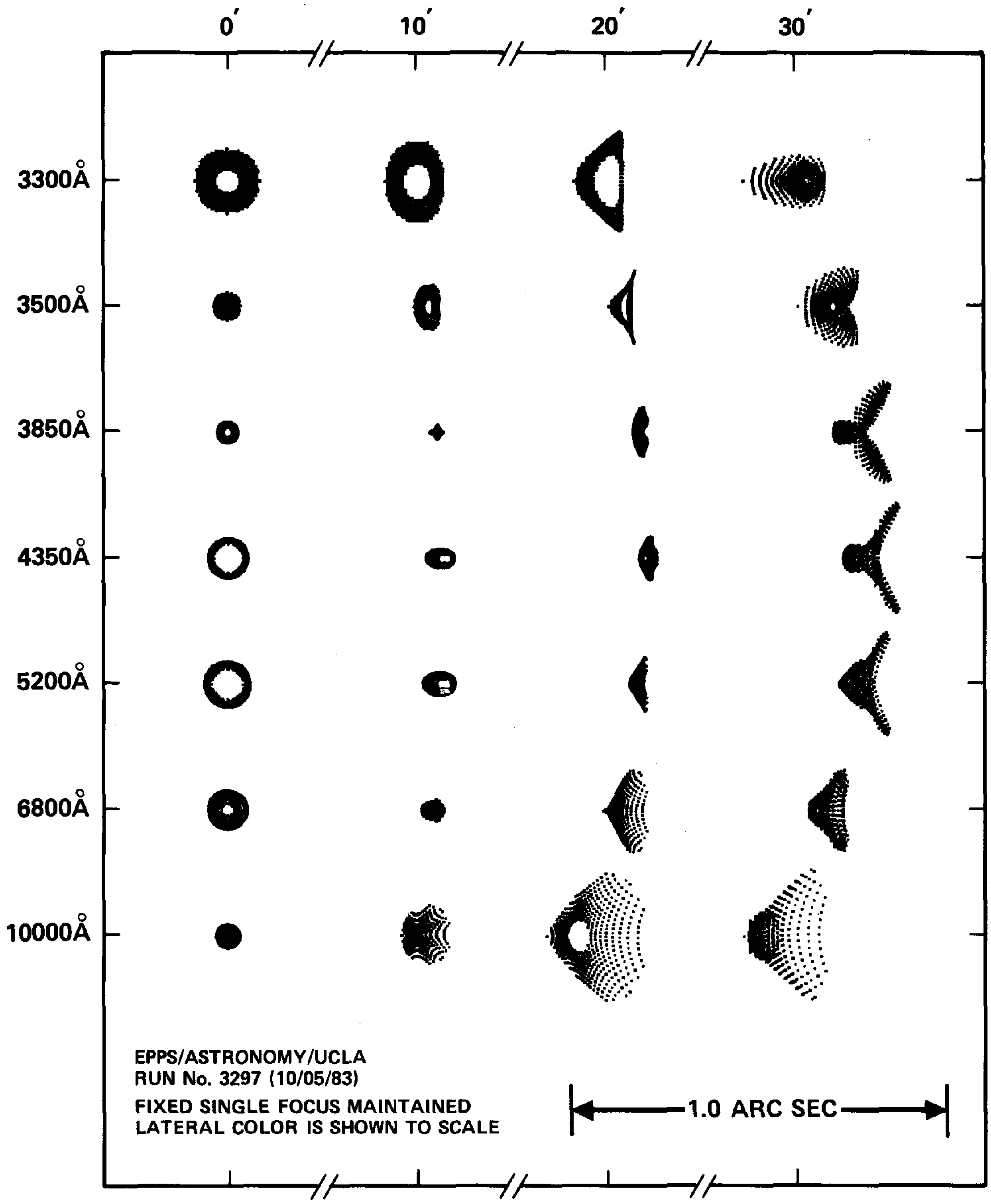
Figure 9



THREE-ELEMENT *f*/6.00 CASSEGRAIN CORRECTOR SYSTEM FOR A 300-INCH TELESCOPE

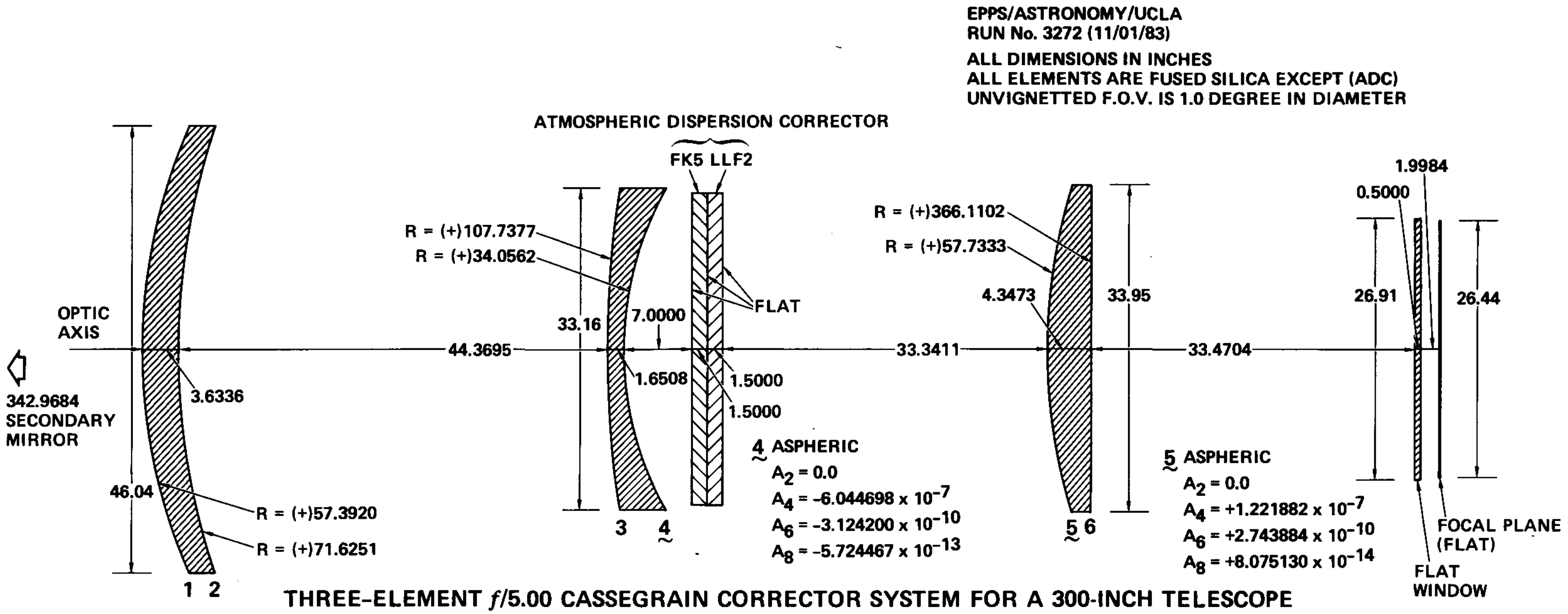
PRIMARY R = (-)1200.0000, A_2 = -1.0000000
SECONDARY R = (-)588.7681, A_2 = -4.9302735
SEPARATION X = (-)417.6794
CLASSICAL *f*/2.00 TO *f*/5.28 NAKED CASSEGRAIN

Figure 10



MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT *f*/6.00 CASSEGRAIN CORRECTOR SYSTEM
WITH AN *f*/2.00 PARABOLIC PRIMARY

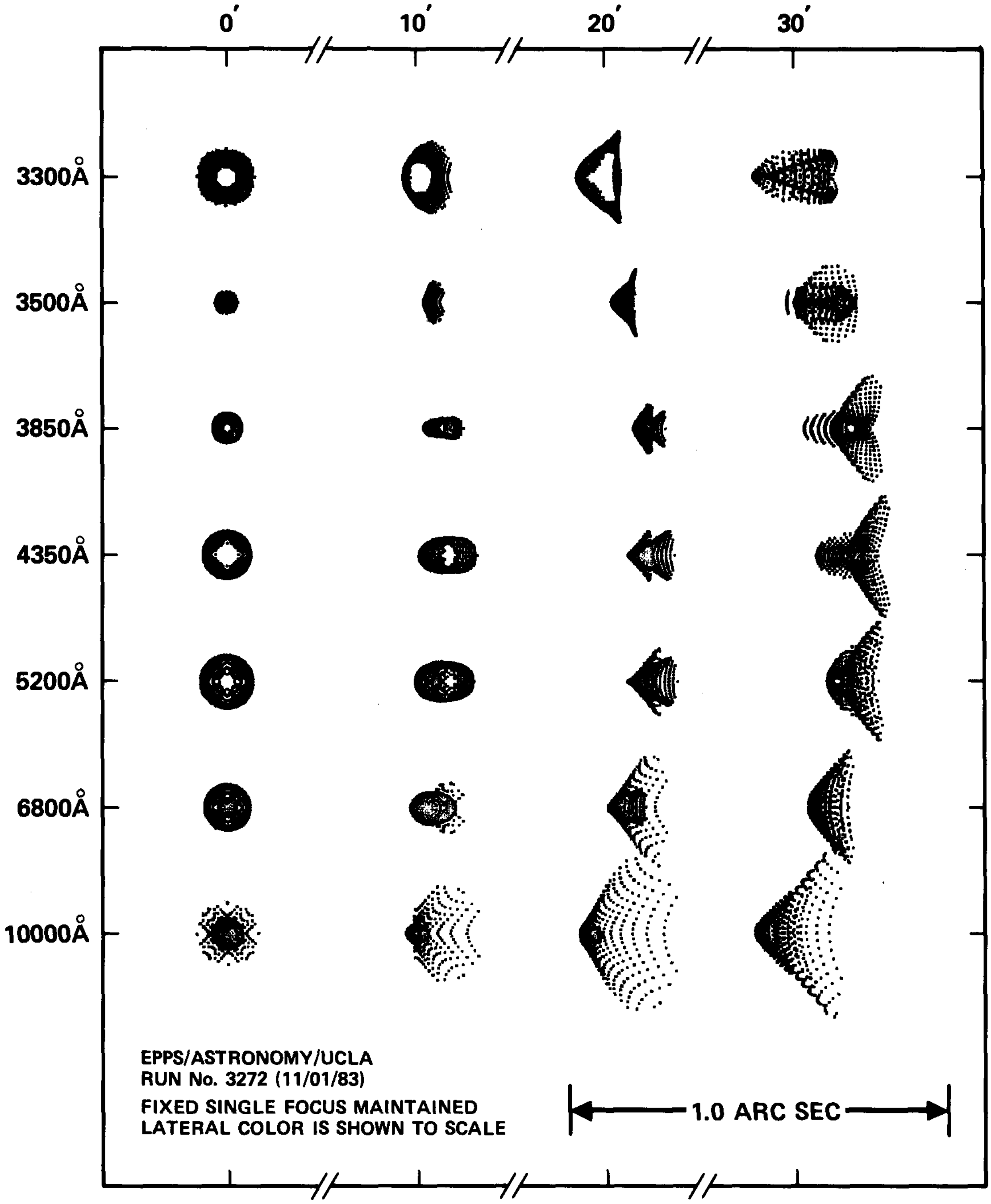
Figure 11



THREE-ELEMENT *f*/5.00 CASSEGRAIN CORRECTOR SYSTEM FOR A 300-INCH TELESCOPE

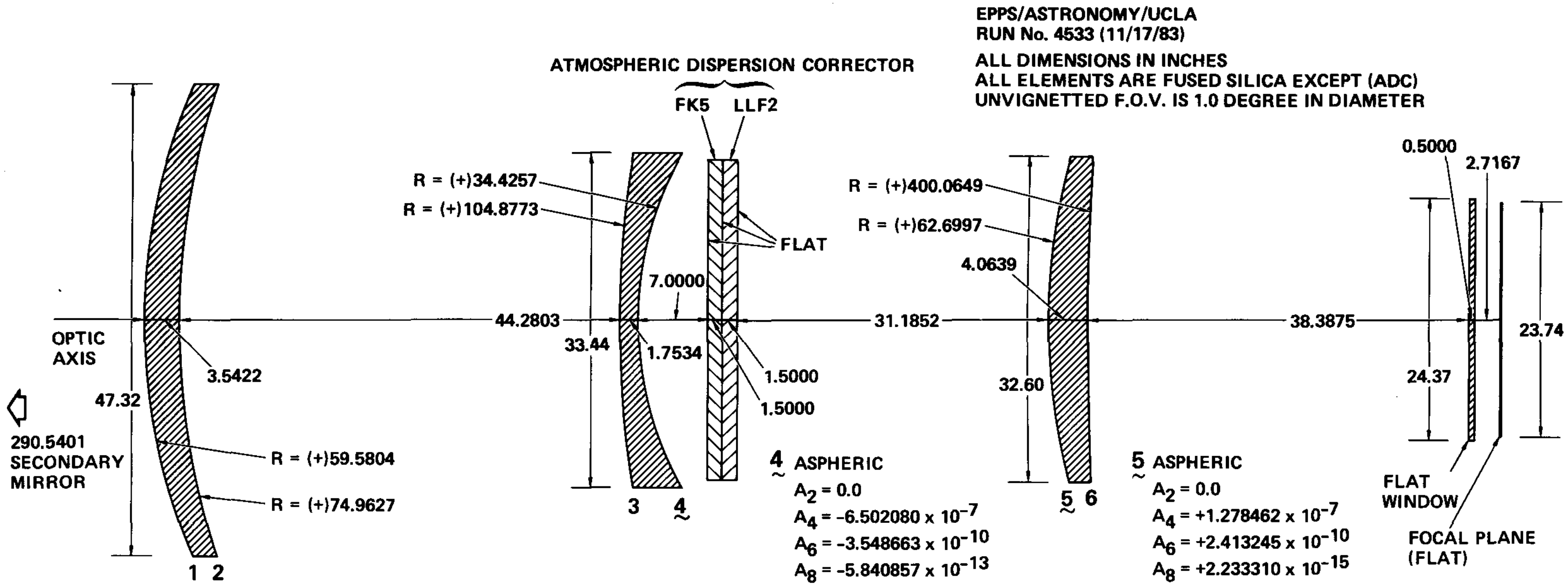
PRIMARY R = (-)1200.000, A_2 = -1.0000000
SECONDARY R = (-)754.7174, A_2 = -6.7533895
SEPARATION X = (-)391.3235
CLASSICAL *f*/2.00 TO *f*/4.50 NAKED CASSEGRAIN

Figure 12



MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT $f/5.00$ CASSEGRAIN CORRECTOR SYSTEM
WITH AN $f/2.00$ PARABOLIC PRIMARY

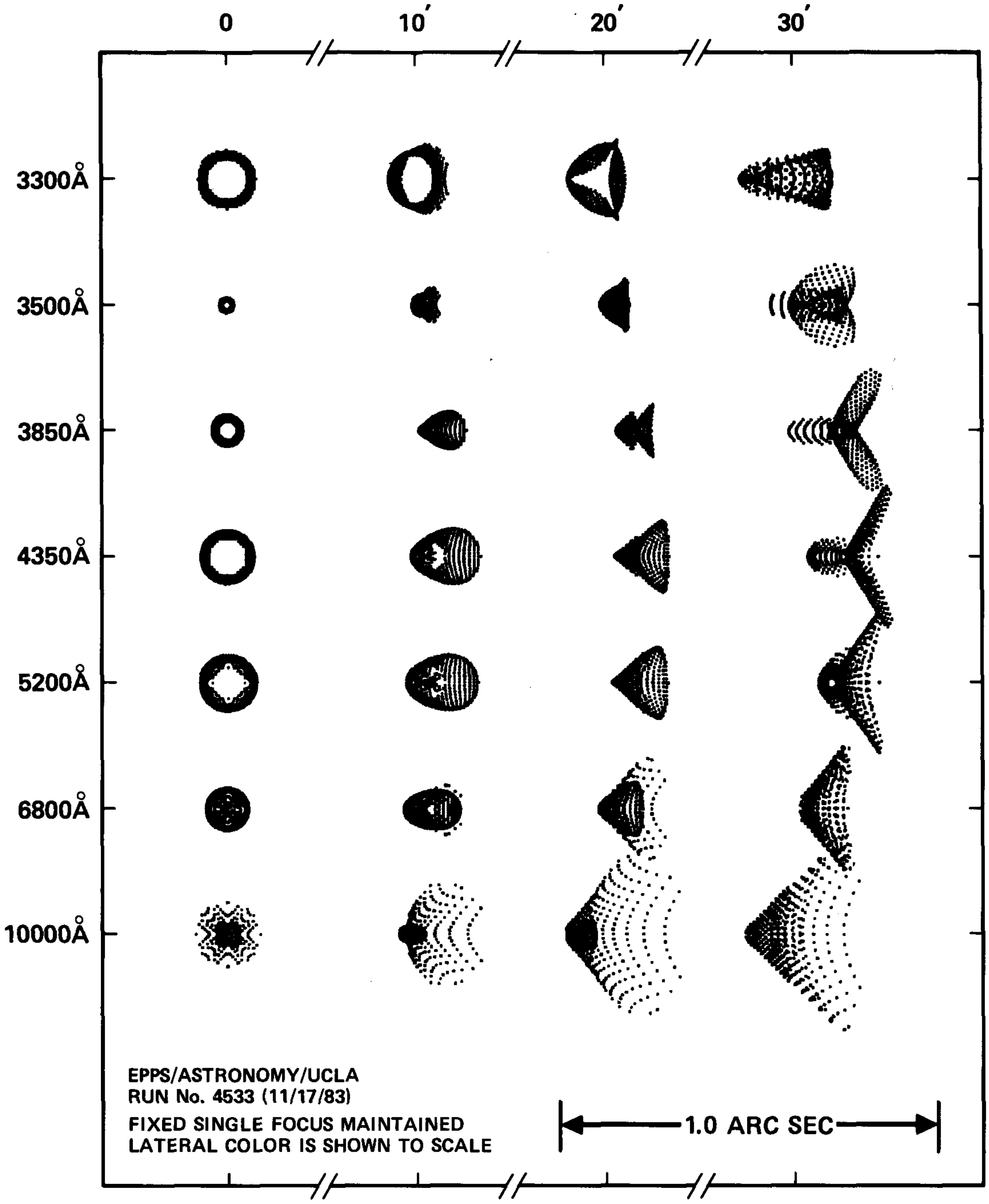
Figure 13



THREE-ELEMENT *f*/4.50 CASSEGRAIN CORRECTOR SYSTEM FOR A 300-INCH TELESCOPE

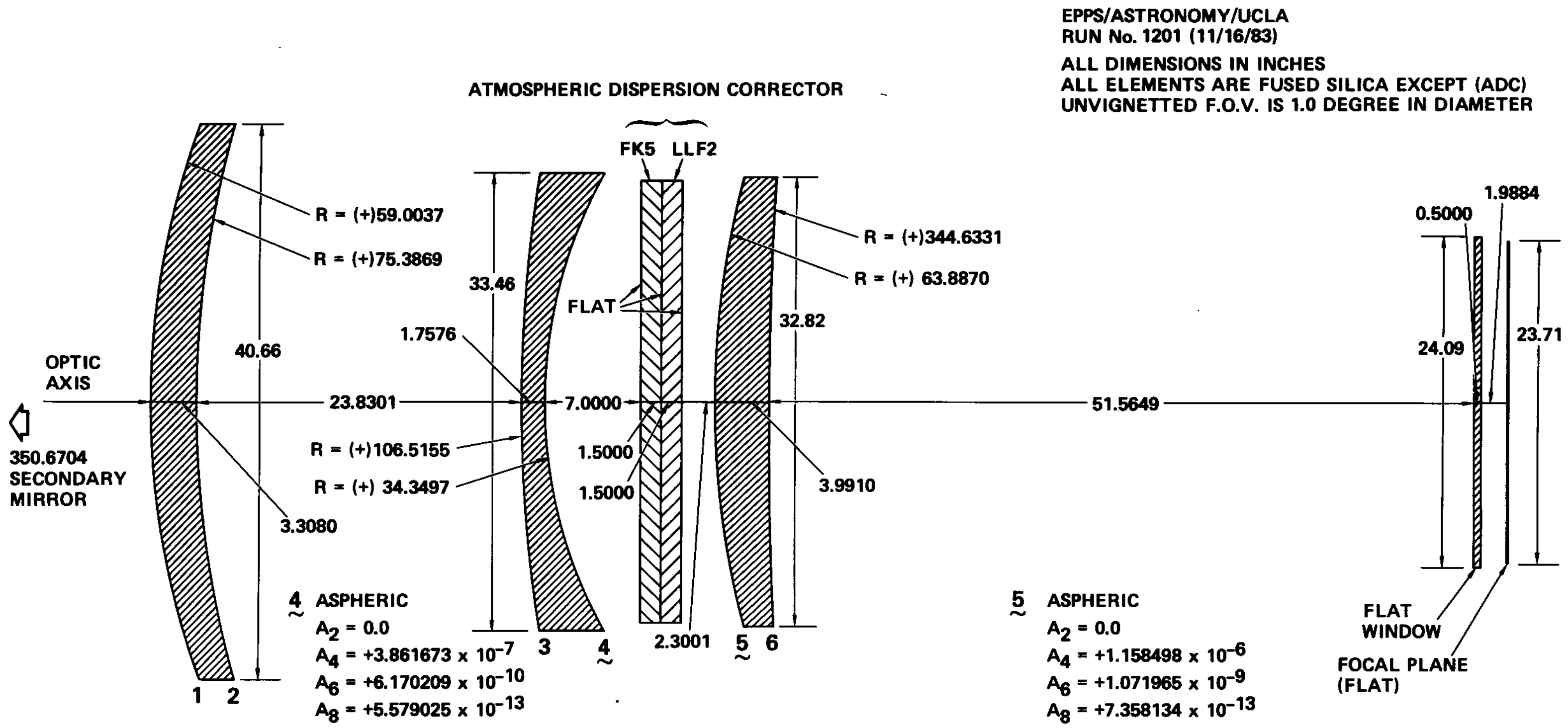
PRIMARY R = (-)1080.0000, $A_2 = -1.0000000$
SECONDARY R = (-)671.9081, $A_2 = -6.6509929$
SEPARATION X = (-)353.8440
CLASSICAL *f*/1.80 TO *f*/4.08 NAKED CASSEGRAIN

Figure 14



MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT *f*/4.50 CASSEGRAIN CORRECTOR SYSTEM
WITH AN *f*/1.80 PARABOLIC PRIMARY

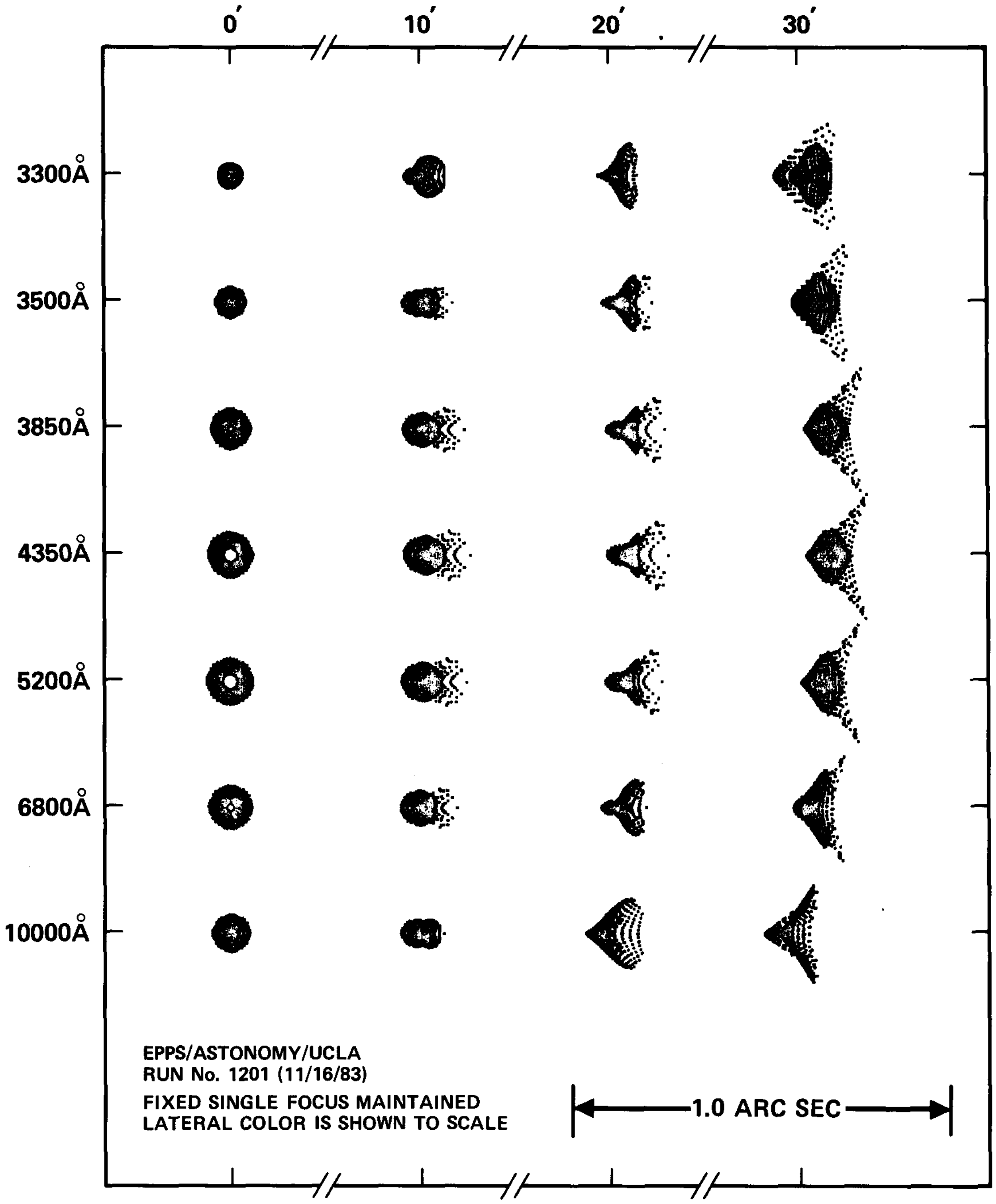
Figure 15



THREE-ELEMENT *f*/4.50 CASSEGRAIN CORRECTOR SYSTEM FOR A 300-INCH TELESCOPE

PRIMARY R = (-)1080.0000, A_2 = -1.1523105
SECONDARY R = (-)639.9724, A_2 = -8.1400813
SEPARATION R = (-)353.6431
HYPERBOLIC *f*/1.80 TO *f*/4.31 NAKED CASSEGRAIN

Figure 16



MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT *f*/4.50 CASSEGRAIN CORRECTOR SYSTEM
WITH AN *f*/1.80 HYPERBOLIC PRIMARY (A_2 = -1.1523105)

Figure 17

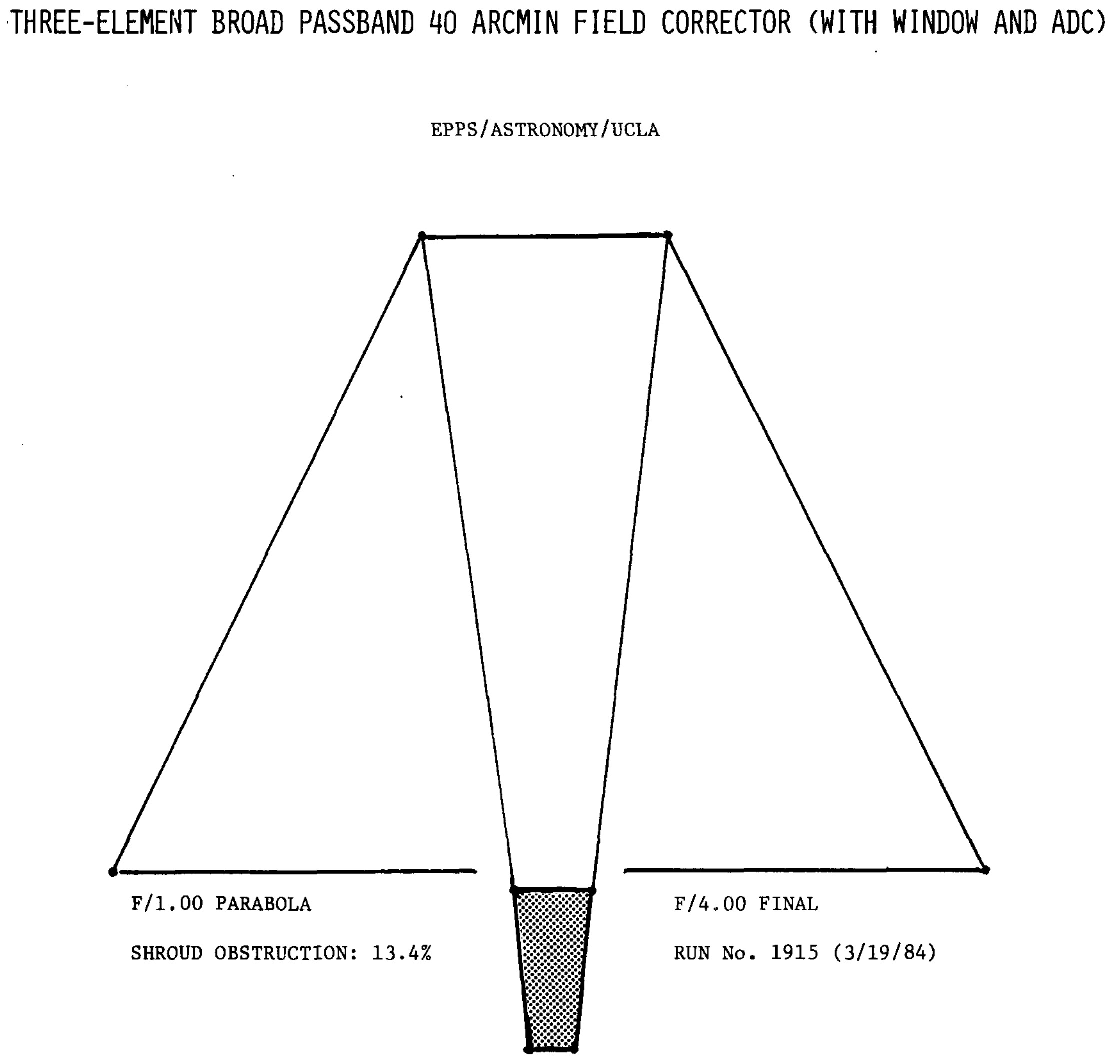
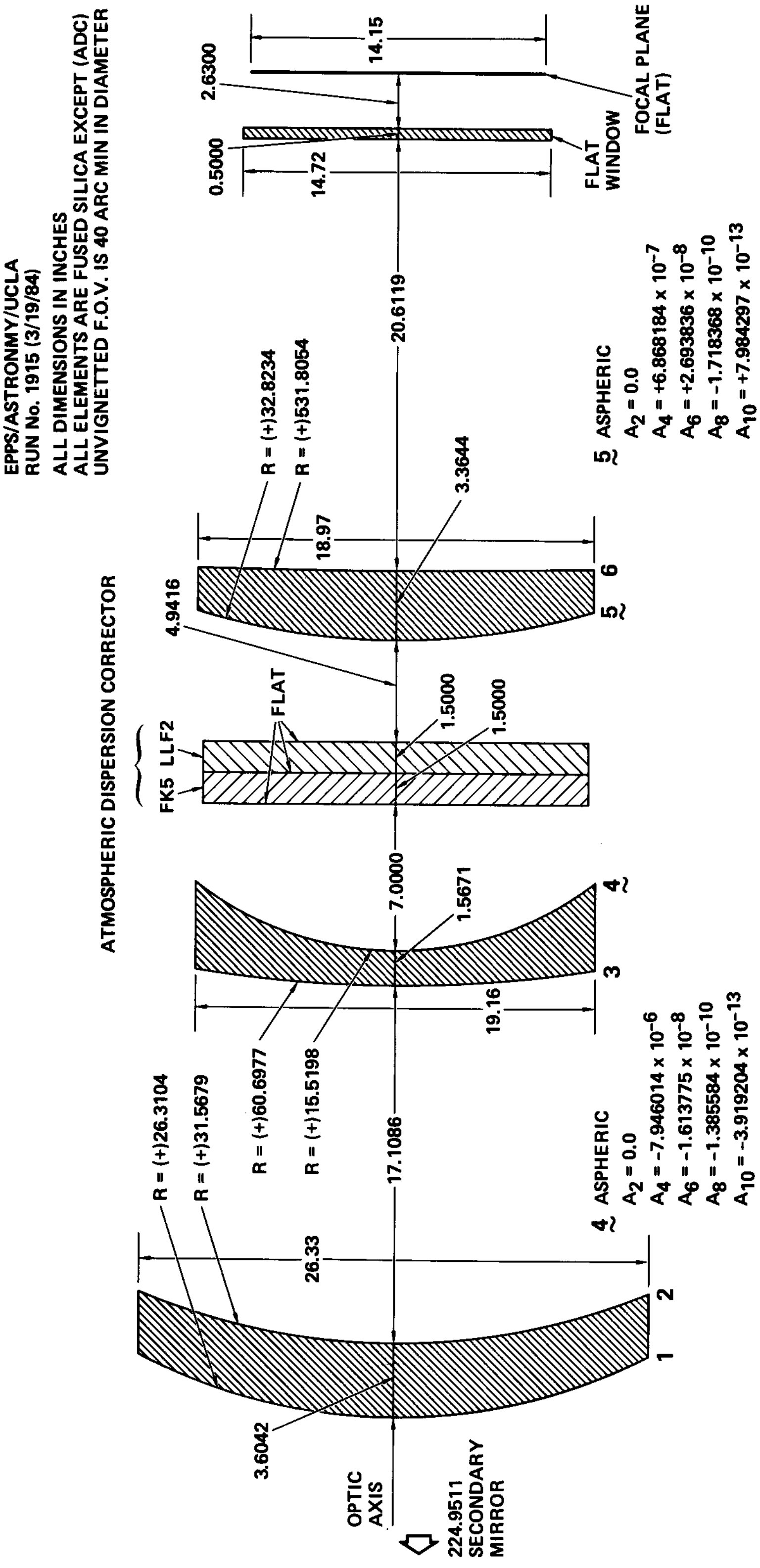

THREE-ELEMENT BROAD PASSBAND 40 ARCMIN FIELD CORRECTOR (WITH WINDOW AND ADC)
EPPS/ASTRONOMY/UCLA
F/1.00 PARABOLA
SHROUD OBSTRUCTION: 13.4%
F/4.00 FINAL
RUN No. 1915 (3/19/84)

Figure 18



THREE-ELEMENT $f/4.00$ CASSEGRAIN CORRECTOR SYSTEM FOR A 300-INCH TELESCOPE

PRIMARY R = (-) 600.0000, $A_2 = -1.0000000$
SECONDARY R = (-) 225.9176, $A_2 = -3.2132642$
SEPARATION X = (-) 219.2153
CLASSICAL $f/1.00$ TO $f/3.52$ NAKED CASSEGRAIN

Figure 19

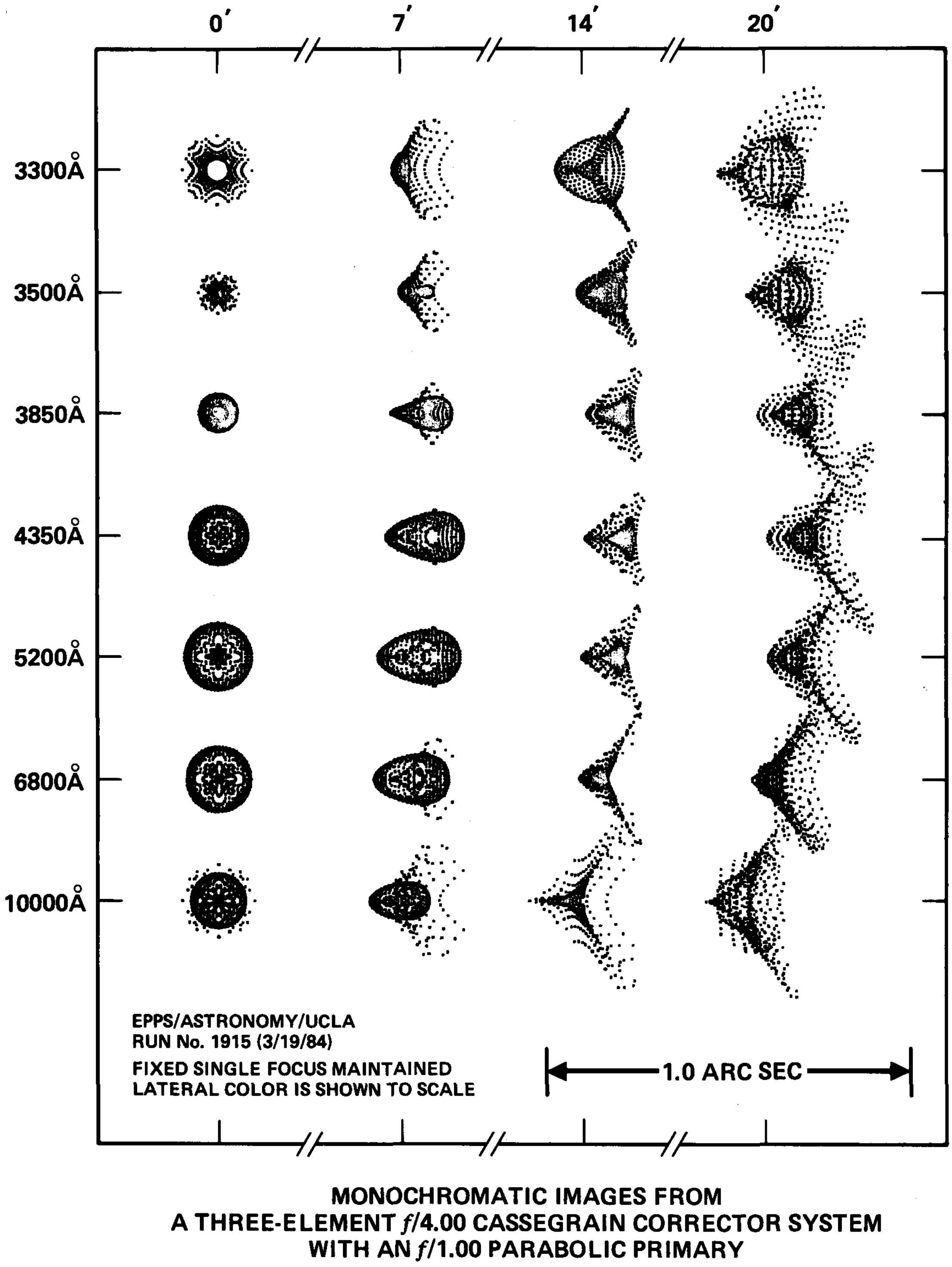

0′
7′
14′
20′
3300Å
3500Å
3850Å
4350Å
5200Å
6800Å
10000Å
EPPS/ASTRONOMY/UCLA
RUN No. 1915 (3/19/84)
FIXED SINGLE FOCUS MAINTAINED
LATERAL COLOR IS SHOWN TO SCALE
1.0 ARC SEC
MONOCHROMATIC IMAGES FROM
A THREE-ELEMENT f/4.00 CASSEGRAIN CORRECTOR SYSTEM
WITH AN f/1.00 PARABOLIC PRIMARY

Figure 20

SUMMARY OF FIELD CORRECTOR GEOMETRY AND OPTICAL PERFORMANCE DATA

	400-INCH UC TMT			300-INCH ARIZONA HONEYCOMB				
	Bf/2	Rf/2	f/5	f/6	f/5	f/4.5	(exH) f/4.5	f/4
FOCAL LENGTH (inches)	800	800	2000	1800	1500	1350	1350	1200
(FLAT) FIELD DIAM (arcmin)	30	30	40	60	60	60	60	40
SHROUD OBSTRUCTION (% area)	~3	~3	14	19	22	22	22	14
SECONDARY DIAM (inches)	---	---	84.7	99.1	112.0	110.6	111.0	85.0
LARGEST LENS DIAM (inches)	33.5	33.5	34.0	47.5	46.0	47.3	40.7	26.3
OVERALL CORRECTOR LENGTH (inches)	57.6	57.1	73.0	150.7	133.3	136.4	99.2	64.3
AVE IMAGE ENERGY IN 1/4 ARSCEC DIAM (%)	81	87	94	97	97	94	100	91
AVE IMAGE RMS DIAM (arcsec)	0.18	0.16	0.13	0.10	0.12	0.13	0.09	0.16
WORST IMAGE ENERGY IN 1/4 ARCSEC DIAM (%)	39	52	60	85	85	80	98	80
WORST IMAGE RMS DIAM (arcsec)	0.33	0.27	0.26	0.18	0.19	0.22	0.12	0.22
PINCUSHION DISTORTION AT FULL FIELD (%)	1.2	1.3	1.3	1.5	1.0	0.7	0.6	1.4
CHROMATIC PASSBAND AT SINGLE FOCUS (F-C) *(FULL RANGE IS 3.30 WITH REFOCUS)	1.71*	1.62	4.63	4.63	4.63	4.63	4.63	4.63
VERGENCE THRU ADC (f/#.#)	2.8	---	6.9	10.1	6.9	6.3	6.9	6.2
MAXIMUM LATERAL COLOR (arcsec)	0.15	0.11	0.09	0.26	0.20	0.18	0.10	0.17
AVE LATERAL COLOR AT WORST FA (+/-arcsec)	0.06	0.04	0.03	0.09	0.07	0.07	0.04	0.06

POTENTIAL PROBLEM AREAS COMMON TO THIS GENERIC CLASS OF BROAD-PASSBAND FIELD CORRECTORS

1. Secondary mirror alignment tolerance are (approximately): decentration < +/-0.003 inches; tilt < +/-5 arcsec. Active monitoring will be required, though open loop correction can maintain residuals of this order in principle.

2. Dimensional stability of the telescope tube structure is essential at the level of +/-0.0002 inches for the UC TMT and +/-0.0005 inches for the Arizona honeycomb. Thermal variations during an exposure could be problematical.

3. Broad-passband high-efficiency transmission coatings will prove essential to satisfactory "thruput" and elimination of internal ghost images.

4. Flatness of the (ccd ??) detector(s) for imaging will prove essential at the level of +/-5μ for the UC TMT and +/-13μ for the Arizona honeycomb.

5. All elements will have to be made thick enough in the final design(s) such that they can be mounted so as to preserve alignment and resist significant (optical) bending under expected variations of gravitational loading.

SUMMARY OF TENTATIVE CONCLUSIONS

A. 400-INCH UC TMT (AND 600-INCH NNTT/SMT)

1. Prime focus 30-arcmin field correctors of limited single-focus passband may (??) be possible for imaging if multiple rear sections and refocus are allowed. The present design falls short of reasonable and desirable optical performance expectations by a substantial margin.

2. Vergence thru a prime focus ADC is extreme and cannot be softened. A counter-rotating pair of zero-deviation prisms may not be viable as a prime focus ADC.

3. If an ADC in the present design can be realized, the design should be reoptimized under more restrictive (passband) conditions for better optical performance in the UV and blue (J-band).

4. Limited-passband correctors as described above are not suitable for multi-object (fiber-fed) spectroscopy.

SUMMARY OF TENTATIVE CONCLUSIONS (Continued)

A. 400-INCH UC TMT (AND 600-INCH NNTT/SMT) (Continued)

5. An internal Cassegrain 40-arcmin broad-passband field corrector for imaging and spectroscopy is possible for the UC TMT, though its focal length is extreme in the present example but could be shortened. This corrector typs is <u>not</u> suitable for imaging in the NNTT/SMT due to excessive focal length.

B. 300-INCH ARIZONA HONEYCOMB (AND 600-INCH EQUIVALENT NNTT/MMT)

1. An external Cassegrain (f/1.8 parabola to f/4.5) 60-arcmin broad passband field corrector meets reasonable and desirable optical performance expectations for both imaging and multi-object spectroscopy.

2. The ADC for the above corrector has been implemented on a preliminary basis BY E. Anderson, Steward Observatory.

3. E. Anderson has also replaced the above ADC with a dispersing prism (for slitless spectroscopy). Loss of image quality is minimal.

4. The secondary mirror diameter above can be reduced significantly by relocating the final focus near the primary mirror vertex.

5. An external Cassegrain (f/1.0 parabola to f/4.0) 40-arcmin broad-passband field corrector, with comparable optical quality and characteristics to the above, offers unprecedented opportunity for compact telescope geometry if the required 300-inch f/1.0 parabolic primary mirror can be manufactured in practice.

6. Expected perturbations, such as removal or thickening of the 0.50-inch-thick window near focus, or reasonable residual decentration and/or tilt of the secondary mirror in the above models, do not degrade optical performance by unacceptable amounts.

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DISCUSSION

J.P. Swings: 1) A few years ago you were "advocating" the Paul-Baker corrector system. What is your reason for working on refractive correctors now? 2) Can you give an idea of the sizes of the optical elements in the correctors you showed and described?

H. Epps: 1) Paul-Baker correctors represent one method of obtaining broad passband wide angular fields. The 72-inch zenith telescope under construction at University of Arizona is an example where their use seems to be desirable.

We are working on refractive correctors as an alternative method of achieving broad passband and wide fields. New designs were required in order to incorporate atmospheric dispersion correction (ADC), to accommodate fast primary mirrors in the range f/2 to f/1, and to improve image quality to a standard represented by attaining 90% or more encircled energy within 1/4 arcsec when averaged over all field angles and colours.

2) The largest lenses required by the design presented here are in the range 26 inches to 48 inches. This data is detailed for each corrector in our data summary table.