

Optical System Design of Solar Blind Ultraviolet Imaging Detector

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Abstract: Solar blind ultraviolet imaging detector is useful in detecting corona of overhead electric transmission lines, reducing power equipment damage. UV lens are the core of solar blind ultraviolet imaging detector. Their property affects the performance of the whole detector directly. In view of the problems of insufficient light energy utilization in corona detection system, the paper proposes a coaxial optical system based on wavelength and light separation, which eliminates the center field, enlarges the aperture of UV objective, and effectively improves the energy gathering ability of corona detection system. The mean square of the designed UV objective full view and whole detection range is less than 0.14mm, meeting the requirement of ultraviolet corona detection resolution. Compared with foreign ultraviolet optical system imaging detectors, the proposed solar blind ultraviolet imaging detector with coaxial optical system has better energy collection efficiency.

I. INTRODUCTION

The physics effect of cosmic rays and formation radioactive material make a small amount of charged ions in the air. The charged ions do directional movement under the action of electric field which forms electrical current. When the electric field intensity increases between transmission equipment to a certain value (generally between 20 ~ 30 kv/cm), the charged ions in the air under the action of electric field get enough energy and make collision ionization with other molecular in the air. A channel with high conductivity is formed, which makes air local breakdown on the surface of high voltage transmission equipment and produces corona discharge [1-4]. Corona discharge can cause singeing, insulator corrosion, power line damage phenomena on transmission equipment surface, and more seriously it may cause power supply accidents. In addition, corona discharge is always with high frequency pulse electromagnetic wave radiation, so it will produce very big interference to radio communications. Therefore, corona blind UV imaging detector, which can make early detection and accurate positioning, is more and more brought to the attention of power sector [5-7]. Solar blind UV imaging detector through field height matches ultraviolet and visible light two channels, and make real-time acquisition of field UV and visible light image. Among them, UV channel works from 240 nm to 280 nm solar blind ultraviolet spectrum. Owing to the strong absorption of ozone in the stratosphere, the spectrum radiation in solar spectrum near the ground is almost non-existent in the atmosphere, so the spectral imaging detection can naturally avoid nature complex background interference. Solar blind UV imaging detector achieves corona early imaging detection making use of the characteristics of blind ultraviolet light contained in corona radiation spectrum. As early as the late 1970 s, foreign countries have carried out the study of ultraviolet radiation light signals. In the late 1990 s, overseas researchers have embarked on solar blind UV imaging detector work, and then they were gradually applied to the market [8-10]. At present, the representative main products include Israel Ofil Company's SuperB, Luminar, and South Africa UVIRCO's CoroCAM series and so on, which is shown in Figure 1.



(a) SuperB (b) Luminar (c) CoroCAM

Figure 1 Typical UV imaging detector products abroad

Although the mentioned above products are of high sensitivity, positioning accuracy, simple operation, and low power consumption, there are many shortcomings. Its ultraviolet system structure is one of the typical faults. UV lens, as blind UV imaging detector core components, mainly affect parameters like optical aperture, light energy utilization, resolution of the detector and field, and its performance directly affects the performance of the detector. Cassegrain system is widely used in Ofil and UViRco company products' ultraviolet optical lens. The center view exists fences, which lead to detector light diameter decrease and insufficient light energy utilization, as shown in Figure 2. This directly causes that when detector is telecommuting, in order to make the probe light energy meet imaging demand, usually require larger primary mirror size. In the aspect of application, the defect is not conducive to products miniaturization development.

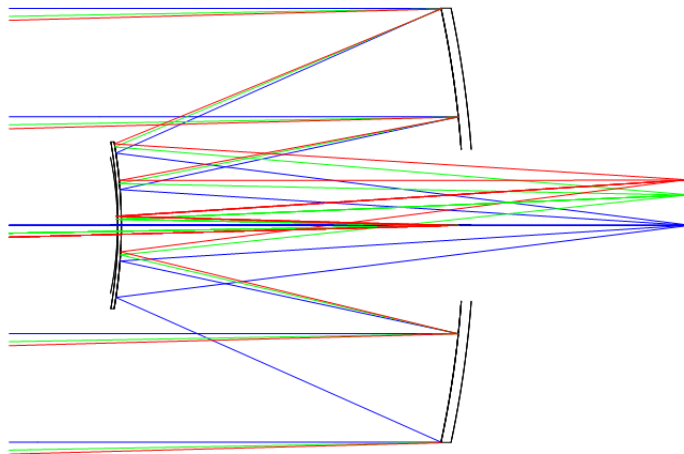


Figure 2 Cassegrain system schematic diagrams

Aiming at these problems, the article designs a kind of coaxial optical system based on color separation spectrophotometry, which eliminates center field fences, increases UV channel optical aperture, and effectively improves the ability of corona detection system energy collection. It provides practical reference for solar blind ultraviolet imaging detectors' wide application.

II. THE DETERMINATION OF OPTICAL SYSTEM PARAMETERS

The technical indicators of solar blind ultraviolet imaging detectors are usually shown in the table below:

Detection distance	Angular resolution	View Angle
3m~ infinity	$\leq 0.1^\circ$	$\geq 6^\circ$

This system adopts UV ICCD diagonal size to 18 mm. Because the "solar blind" ultraviolet light from corona discharge is extremely weak, provide greater incident luminous flux to UV ICCD than

or equal to $1 \times 10^{-17} \text{W}$ to make UV ICCD light energy of incident satisfy the need of imaging. Target emitted radiation incidence after UV lens and filters to UV ICCD radiation flux can be calculated by the following formula:

$$\Psi = \int_{240}^{280} k \frac{\pi D^2}{4} \frac{I(\lambda)}{L^2} \tau_{\text{filter}}(\lambda) \tau_{\text{lens}}(\lambda) \tau(\lambda)^{L/1000} d\lambda$$

In it, D is UV objective light aperture, L is the distance of the target to ultraviolet lens first surface, k is the related detection Angle coefficient, τ_{filter} and τ_{lens} are filter and UV objective transmittance respectively, $\tau(\lambda) L/1000$ is atmospheric attenuation coefficient.

In this system, the half width of UV band pass filter transmittance is about 0.21, the ultraviolet lens overall transmittance designed is greater than or equal to 0.8. Through the design requirements' view Angle indicators, the normal Angle between actual detection objects and the detector is small, and can be thought as $k = 1$ when calculating.

When parameter $k = 1$, $\tau_{\text{filter}} = 0.21$, and $\tau_{\text{lens}} = 0.8$ to the type, we can get:

$$\Psi = \frac{\pi D^2}{4} \times 0.21 \times 0.8 \times \int_{240}^{280} \frac{I(\lambda)}{L^2} \tau(\lambda)^{L/1000} d\lambda$$

When detected minimal ultraviolet sensitivity is $3 \times 10^{-17} \text{W/cm}^2$, combine with the above mentioned UV ICCD flux demand 10^{-17}W ; ultraviolet lens optical aperture size meeting the demand of imaging can be calculated:

$$D \geq 50.215 \text{mm}$$

In order to ensure the quality of imaging, at the same time, consider the size space and mechanical structure, and the final design of diameter size is 52 mm.

UV lens focal length can be got through the size of UV ICCD and system's optical field Angle calculation, which is shown as follows:

$$f' = \frac{d}{\tan 2\omega'}$$

In it, d is ICCD diagonal dimension, and $2\omega'$ is system optical viewing angle.

The ultraviolet lens focal length calculated is $f' \leq 171.73 \text{mm}$. From comprehensive consideration, finally the selected system focal length is 160 mm.

In corona detection system, optical channel is used to detect the background image, and the image channel hope to keep the details of background image as much as possible. The "solar blind" UV channel is only used to detect whether there is phenomenon of corona discharge, and the image characteristics are mottled corona discharge area and no specific information in morphology of temporal images, so "solar blind" UV channel imaging does not care about content details, and concerns only light energy as well as imaging resolution. When 80% imaging dispersion spots in two corona discharge points do not overlap, the subsequent image processing system can separate two points through simple image processing algorithm. By system angular resolution requirements and system focal length, calculated 80% UV objective imaging dispersion spot radius r meet:

$$r \leq \frac{f' \times \Delta\theta}{2}$$

Input the designed ultraviolet lens focal length and angular resolution demand, r is less than or equal to 0.14 mm.

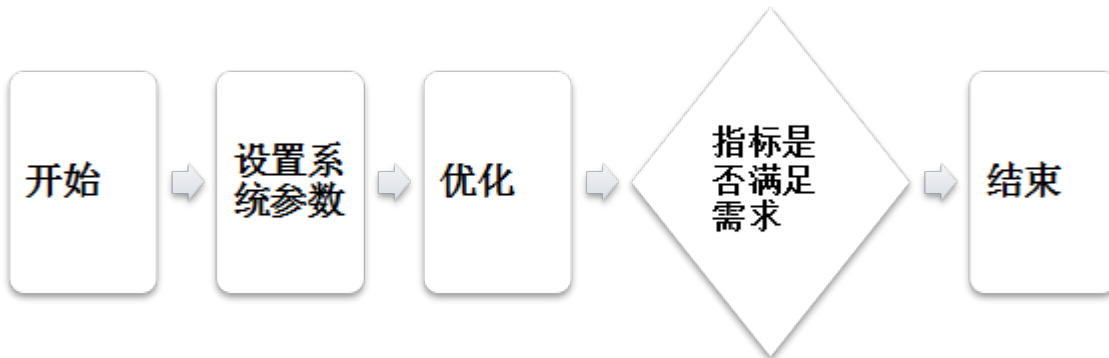
To sum up, the designed UV lens specifications are as follows:

Optical aperture	52mm
Optical acuity field Angle	$\geq 6^\circ$

Detection range	3m~infinity
Working band	240-280nm
System focal length	160mm
Dispersion spot radius	≤0.14mm

III. UV LENS DESIGN

Optical materials transmittance mostly decreases with work wavelength reduction, thus lens material can be used to work for solar blind ultraviolet band is less. Commonly used materials are fused quartz and calcium fluoride. For calcium fluoride materials, the prices are more expensive and are in 240 ~ 280 nm wavelength range. Calcium fluoride shows stronger intrinsic birefringence, which seriously affects the resolution of the system [23]. Due to narrower actual working band, color difference is small, so the system uses fused quartz in the design as lens material. Due to "solar blind" ultraviolet light from corona discharge energy is weak, in order to avoid too many lenses leading to excessive energy loss and saving the cost of system at the same time, use less lens as far as possible when design to meet the system requirements, so adopt the method of splitting monolithic lenses for UV lens design. The designed steps are shown in the Figure below.

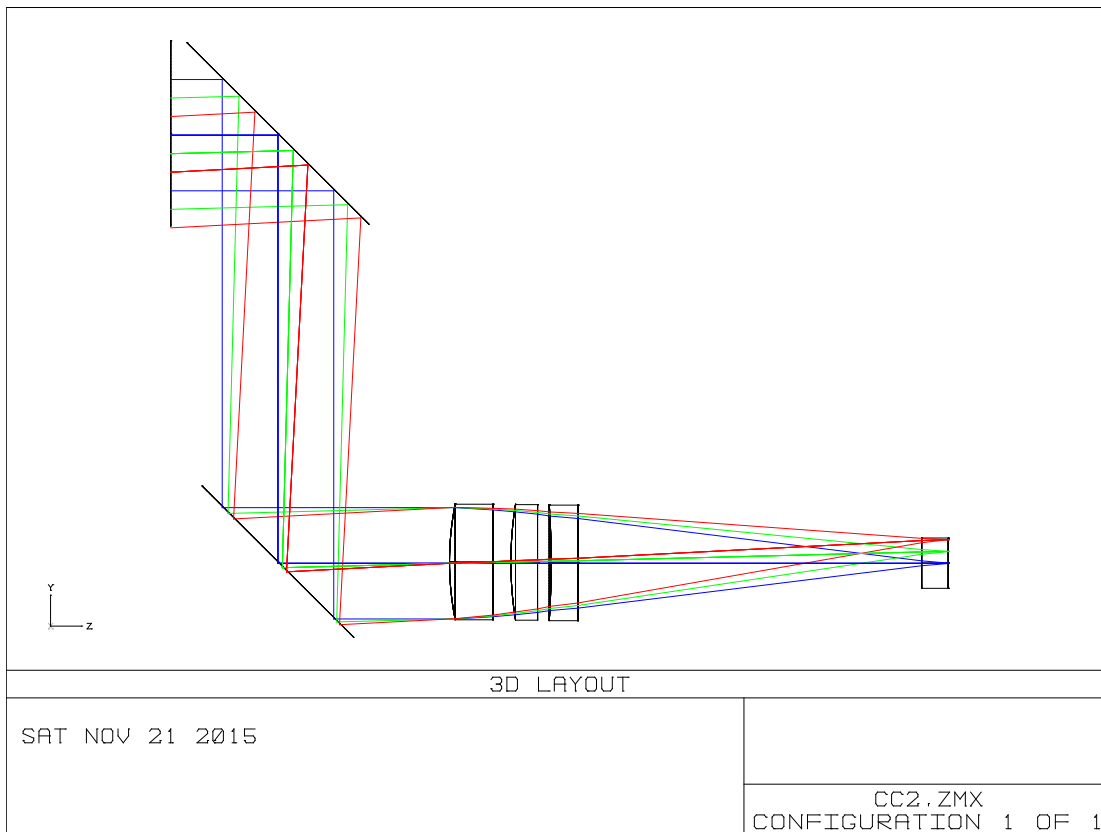


The final

design results are follows:

Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic
OBJ	Standard		Infinity	Infinity		Infinity	0.000000
1	Standard		Infinity	50.000000		43.294567	0.000000
2	Coordinate S...		0.000000		-	0.000000	
3#	Standard		Infinity	-200.000000	MIRROR	60.000000	U 0.000000
4	Coordinate S...		0.000000		-	0.000000	
5#	Standard		Infinity	80.000000	MIRROR	50.000000	U 0.000000
STO*	Standard		139.563741	20.272840	F_SILICA	27.000000	U 0.000000
7*	Standard		Infinity	8.340345		27.000000	U 0.000000
8*	Standard		169.895708	12.404471	F_SILICA	27.000000	U 0.000000
9*	Standard		1.548053E+004	6.379813		27.000000	U 0.000000
10*	Standard		-416.108899	12.389301	F_SILICA	27.000000	U 0.000000
11*	Standard		2707.931131	160.371999		27.000000	U 0.000000
12	Standard		Infinity	12.500000	F_SILICA	11.759993	0.000000
13	Standard		Infinity	0.000000		11.354303	0.000000
IMA	Standard		Infinity	-		11.354303	0.000000

System structure diagram is as follows:



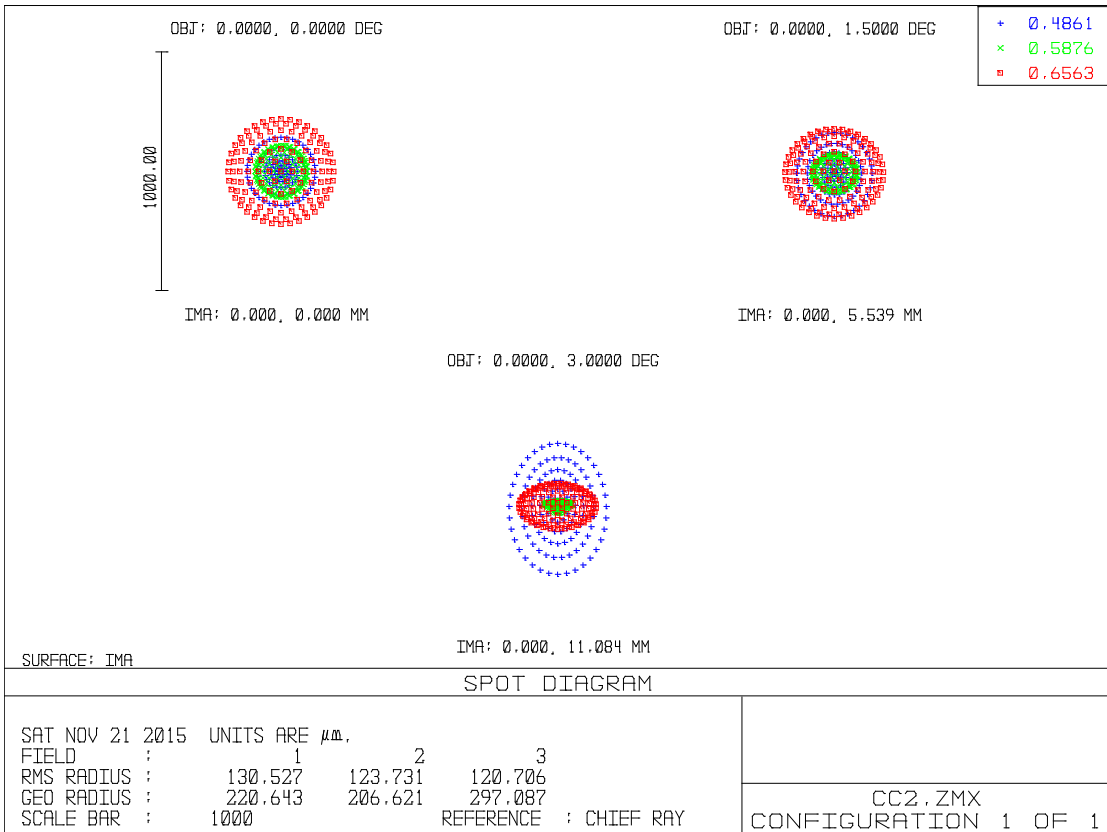
In the diagram, 1 reflector is spectral dichroic mirror surface, which is used to divide visible and ultraviolet light emitted from the target, and achieves UV-vis double path detection. Planes 12 and 13 are ultraviolet band pass filters, and UV ICCD image plane overlaps 13 planes. At the same time, ultraviolet lens can move as a whole through mechanical focusing structure to implement the target detection from 3 m to infinity.

IV. UV OBJECTIVE ANALYSIS

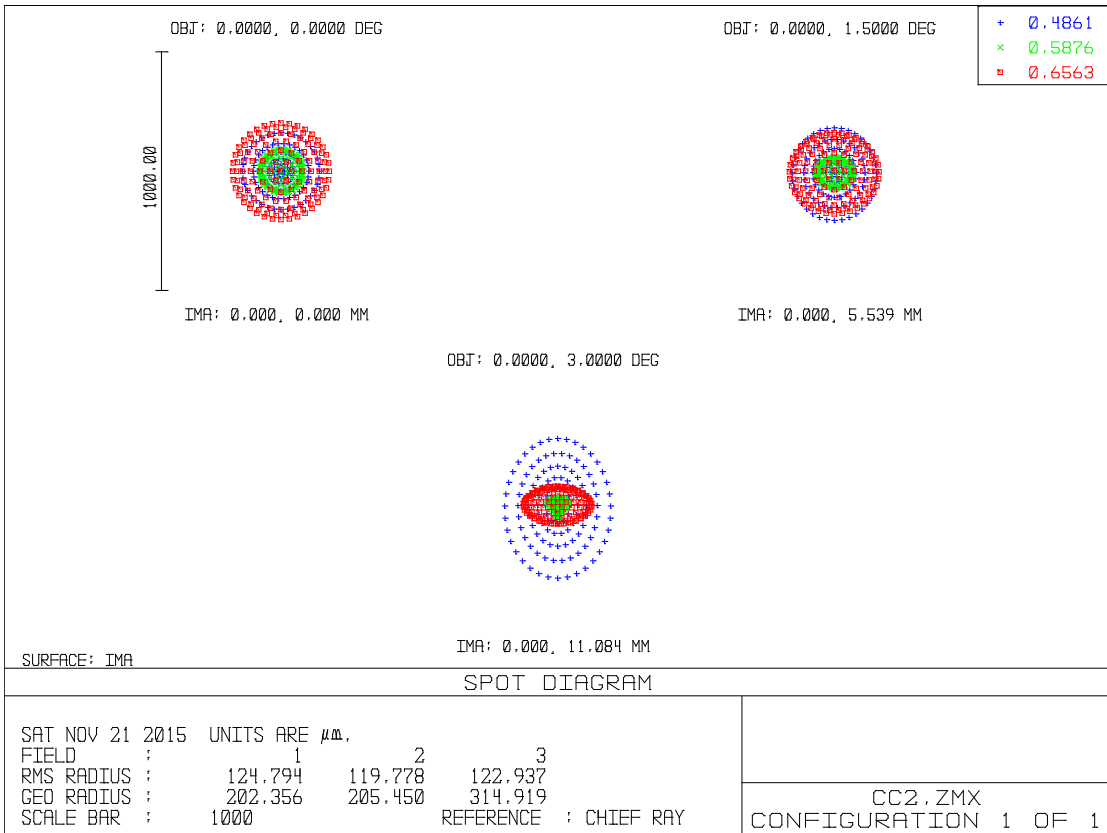
A. Ultraviolet image quality evaluation:

In corona detection system, optical system of UV channel is the system for target signal energy detection, and the energy concentration of the system is the key index of evaluation system image quality [24]. In aberration system, column point's distribution can represent energy distribution, and the intensity of points can measure the merits of the system imaging quality. So energy detection system often uses column points as evaluation standard for the system.

The below diagram is each field's imaging point series when detection range is 3 m and infinity respectively. It can be seen from the diagram that in the whole detection range, the system's each field dispersion root mean square radius is less than 0.14 mm, which meets the design requirements.



3 m



Infinity

B. UV lens tolerance

There are optical element processing and errors between practical optical system design and theoretically designed optical system, which change and reduce the actual performance and image quality evaluation only reflects UV lens imaging quality in ideal theoretical design. So when the

theory design of the optical system meets the requirements of technical indicators, make preliminary tolerance parameters according to manufacturing and assembly capacity, and make tolerance analysis. Through the tolerance analysis of system, find out system sensitivity of tolerance, strictly control influence tolerance, and at the same time, set tolerance compensation reasonably to improve the tolerance of the system. And ultimately determine tolerance parameters in the system, and provide guidance for the subsequent mechanical design.

Comprehensively consider optical lens production level and laboratory assembly capacity, and eventually make the tolerances. It is shown in the following table. Optical component tolerances refractive index is set as 0.0001, and abbe number tolerance is 0.1%.

Su	Components machining tolerance			Assembly tolerances			
	Surface shape tolerance (λ)	Radius of tolerance (N)	Thickness tolerance (mm)	Element wedge (mm)	Spacing tolerance (mm)	Eccentric tolerance (mm)	Tilted tolerance (')
6	0.25	2	0.05	0.05		0.05	2
7	0.25	2			0.05		
8	0.25	2	0.05	0.05		0.05	2
9	0.25	2			0.05		
10	0.25	2	0.05	0.05		0.05	2
11	0.25	2			焦距调节		

Use Monte Carlo simulation method for tolerance sensitivity analysis, and finally the results are as follows:

Point series figure root mean square radius optimal value (mm)	0.115735888
Column chart root mean square radius worst point (mm)	0.115766229
Point column figure root mean square radius average (mm)	0.115749666
90% mean square root radius maximum (mm)	0.115763594
Former focal length offsets (mm)	0.115301mm
Latter focal length offsets (mm)	0.066264mm

It can be seen that 90% of the shots are able to meet the design requirements in the final set within the limits of tolerance, therefore, UV lens can be machined and assembled based on the tolerance. Compared with foreign reflection type design, transmission design has more advantages on light energy utilization.

Light energy utilization	
Reflection type	71%
Transmission type	80%

V. CONCLUSION

This paper analyzes corona detection demands, puts forward the general design demand of

ultraviolet lens, and designs UV lens applied to testing system through splitting method. Within 6° field, the designed UV lens's point column figure mean square root are less than 0.14 mm when imaging range is from 3 m to infinity, which meets the demand resolution of ultraviolet corona detection. At the same time, combining with laboratory existing processing and assembling ability, tolerance analysis of the whole optical system is given. This paper's design of lens can meet the application demand of ultraviolet corona detection.

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