Optical Subsystem for CubeSat Missions

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ABSTRACT

The CubeSat program has facilitated space access for students for over a decade through the innovative design of versatile, and inexpensive research platforms. However, what started as an initiative for academic institutions to be able to data gathering platforms that can be cheaply and rather quickly assembled and launched, has now revolutionized the way even more established agencies look at orbital and space exploration. The mission type determines the payload and capabilities a CubeSat must have. Standard size of a 1U CubeSat is 10 cm x 10 cm x 10 cm. Due to the small dimensions of the pico-satellite, new innovative subsystem designs must be used to accomplish similar mission parameters that larger platforms perform with ease. This paper presents the design and optimization of a payload originally designed for ROARSAT, a larger 3U satellite of dimensions 10 cm x 10 cm x 30 cm developed at Florida International University. This is accomplished by arranging a set of achromatic lenses with a determined focal length to shrink the overall size of the system, while at the same time providing greater magnification of the imaged object.

Keywords

CubeSat; Optical System; Lens; Focal length; Magnification

NOMENCLATURE

f	Focal Length, mm
BFL	Back Focal Length, mm
d_i	Image Distance, mm
d_o	Object Distance, mm
h_i	Image Height, mm
h_o	Object Height, mm
d	Lens Separation, mm
M	Magnification Factor
S	Sensor Area, mm^2
n	Number of Pixels
A	Aspect Ratio

1. INTRODUCTION

The CubeSat standard has spurred the development of small spacecraft missions along with recent advances in technology miniaturization. Consequently, the space industry that mainly produced large, sophisticated aircraft developed by a large team of engineers, has started to change and opt for smaller platforms radically [1]. This has opened opportunities for small commercial and academic institutions to develop spacecraft and its missions. Most of the CubeSat missions focus on earth imaging, but other applications such as attitude calibration, proximity monitoring, star tracking [2], and exo-planet tracking [3] have also been presented.

Most CubeSat designs use two types of optical systems. Refractive systems use a single lens or a combination of lenses to achieve the desired resolution and magnification [4]. Reflective optical systems use a combination of mirrors for the same effect. Both types of optical systems have their advantages. In one hand, refractive optical systems have lower tolerances when it comes to the alignment of the optical elements. In the other hand, reflective systems tend to be more compact [5].

The proposed design is an optimization of a single lens optical subsystem developed by the ROARSAT team. ROARSAT is a 3U pico-satellite developed by fellow members of the Near Earth Explorer (NEE) student club at Florida International University (FIU). The ROARSAT team entered the 2016 FUNSAT competition sponsored by NASA and organized by the Florida Space Grant Consortium (FSGC) where they placed first runners up [12].

This paper is organized as follows: NEESAT's mission is elaborated in section 3. In this section, relevant values such as desired resolution, and object distance are determined. Section 4 discusses the parameters for the design and optimization of the optical system, a detailed account of the manufacturing of the design, and finally a description of validation techniques used to test the optical system. In section 5 offers a discussion of cost and weight estimates for the system. This section is followed by a sections 6, 7 and 8 which includes a conclusion, acknowledgments, and references respectively.

2. PROBLEM STATEMENT

NEESAT's mission is designed to be carried out from a low earth orbit (LEO). From this LEO NEESAT is to photograph the earth's surface and the atmosphere to gather various types of data. This data includes determination of ocean levels, and animal migration patterns; meteorological studies such as cloud formations, and tropical storm tracking; and finally, detection of hazards to human life caused by various natural phenomena. To accomplish this mission, NEESAT's payload includes various off the shelf commercial components as well as a custom optical design. Off the shelf items include a complementary metal-oxide-semiconductor (CMOS) sensor with a through the lens (TTL) camera for which optics were modified to accommodate the new optical design. A plan to incorporate a thermal camera and an HD camera is also being considered but has not yet been implemented. The TTL camera must capture an area of 25 km x 25 km from 600km above the surface of the earth, and the other cameras should also have similar capabilities.

3. OPTICAL SYSTEM DESIGN

3.1 Single Lens System

The system developed by the ROARSAT team could focus on to an area with an h_o of 25km, and because they had a ¼ inch format sensor, they decided to use an image height (h_i) of 6.35mm. The d_o of 600km is determined by the LEO that the satellite will assume. All the parameters for the design of this system are predetermined except for d_i and f. These are critical values because they determine whether the system will fit inside the confined space provided by the 3U platform. To determine these parameters, following calculations were made.

Using the magnification equation

$$M = \frac{-h_i}{ho} = \frac{d_i}{d_o} \tag{1}$$

Notice that the negative sign means that the image will be inverted. Solving for d_i we get

$$d_i = \frac{-h_i d_o}{h_o} \tag{2}$$

From the lens equation, we can say that

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \tag{3}$$

Since $d_0 \gg d_i$ we can say that $d_i = f$. Therefore, the focal length of the system is 152.4 mm.

The system was designed in SolidWorks the assembly can be seen in Figure 1. It features a 159.1 mm long carbon fiber tube with an outer diameter of 35mm and an inner diameter of 30mm. It also has a 5mm by 6.7mm fitting for the lens. This design could fit inside a 3U satellite but not a 1U. Therefore, optimization of the system was necessary.

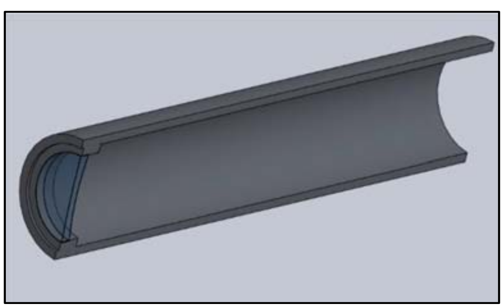


Figure 1. ROARSAT Optical Design

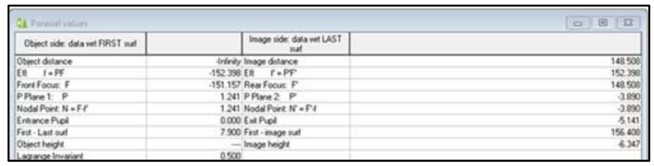
3.2 Single Lens System Simulation

A simulation was run for this system to verify this data. The software used was WinLens3D. This is a free software developed by Qioptiq [6]. It is very easy to use and has a vast library of materials each with their respective properties.

The lens chosen for this system was an Edmund achromatic doublet that was modeled from the manufacturer specifications but slightly modified to have a 152.4mm focal length for simulation purposes [7]. Its diameter is 25mm and maximum aperture is 24mm. Lens parameters can be seen in Figure 2.

Figure 2. Lens Parameters for Simulation of ROARSAT Optical System

The results for this simulation can be verified in the paraxial system table as seen in Figure 3.



Object side: data wrt FIRST surf		Image side: data wrt LAST surf	
Object distance	-Infinity	Image distance	148.508
Efl f = PF	-152.398	Efl f' = P'F'	152.398
Front Focus: F	-151.157	Rear Focus: F'	148.508
P Plane 1: P	1.241	P Plane 2: P'	-3.890
Nodal Point: N = F-f'	1.241	Nodal Point: N' = F'-f	-3.890
Entrance Pupil	0.000	Exit Pupil	-5.141
First - Last surf	7.900	First - image surf	156.408
Object height	—	Image height	-6.347
Lagrange Invariant	0.500		

Figure 3. Paraxial System Values for ROARSAT system simulation

3.3 Compound Optical System

It is to be noted that ¼ inch is not really h_i nor is it the size of the sensor. This measurement is a generalized parameter to categorize certain types of sensors. To calculate the new h_i the number of pixels, the image size and the pixel size need to be considered. The maximum image size that the sensor can produce is $640 * 480$ pixels, it means that the sensor has a total of 307200 pixels, and an aspect ratio of 4:3. Each pixel has an area of $5.6\mu m * 5.6\mu m$ so this means that the total sensor area is $9.634 mm^2$ [8]. The exact height of the sensor can be obtained by using the following formula:

$$h_i = \sqrt{\frac{S}{A}} \tag{4}$$

This is acceptable BFL for the 1U satellite. But the BFL is not the only parameter that needs to be improved by adding another lens we can further reduce the spherical and chromatic aberrations [10]. That is the main reason why it was decided to build a system with compound achromatic doublets.

To determine the focal lengths of the individual lenses the following formula was used.

$$BFL = \frac{f_2(d - f_1)}{d - (f_1 f_2)} \tag{5}$$

Since the BFL is known, but f_1 and f_2 are not. This calculation was done iteratively in excel. Table 1. shows the results. The values for f_1 and f_2 that were used are for commercially available 25mm achromatic doublets. It is also to be noted that to save space d was kept at a minimum of 1mm.

Table 1. Optimal Lens Choices for a Compound

Optimal choices for compound optical system											
di1	do1	f1	M1	d imput	di2	do2	f2 imput	M2	Mt	ho imput	hi
150	6.00E+08	150	-2.5E-07	1	59.83936	-149	100	0.40161	-1.004E-07	2.50E+07	-2.51
175	6.00E+08	175	-2.9E-07	1	63.50365	-174	100	0.36496	-1.064E-07	2.50E+07	-2.6612
300	6.00E+08	300	-5E-07	1	63.11346	-299	80	0.21108	-1.055E-07	2.50E+07	-2.6385

The closest choice for this system is one with lenses of f_1 of 175mm and f_2 of 100mm. Figure 4 shows a Solidworks design of the system that was analyzed. It features an optical tube with an outside diameter (OD) of 35mm and an inside diameter (ID) of 30mm. To mount the lenses short sections of a 30mm OD and 25mm ID are cut to the edge thickness dimensions and fitted into the tube. To assemble the system tubes, the tubes must be cut in half then the lens can be mounted. The system then can be sealed by a clamp. The material is carbon fiber to make the design as light as possible.

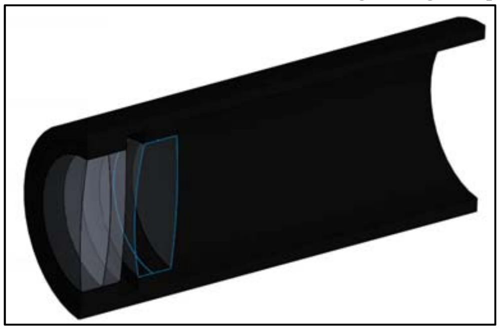


Figure 4. Section View of Compound Lens System

3.4 Compound Lens System Simulation

A simulation was run on WinLens3D with the same parameters as for the ROARSAT but with different lenses. The results of this simulations are concordant with the theoretical calculations. Figure 5a and Figure 5b depict the lenses chosen for the simulation and their respective effective focal lengths (EFL).

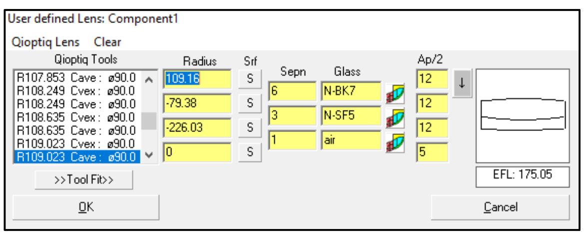


Figure 5a. Lens 1 Parameters

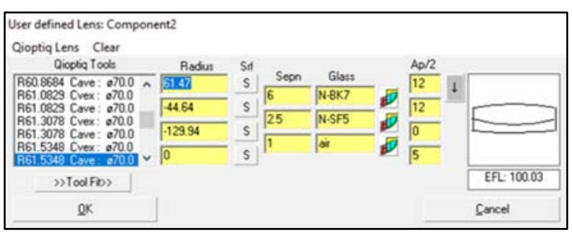


Figure 5b. Lens 2 Parameters

A paraxial graph for the simulated system is shown in Figure 6. The paraxial values for such simulation can be seen in Figure 7.

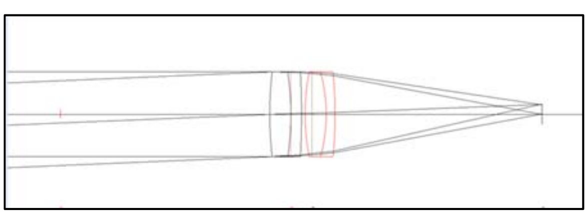
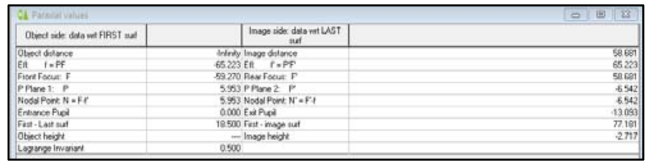


Figure 6. Compound Optical System Paraxial Simulation



Object side: data wrt FIRST surf		Image side: data wrt LAST surf	
Object distance	-Infinity	Image distance	58.681
Efl f = PF	-65.223	Efl f' = P'F'	65.223
Front Focus: F	-59.270	Rear Focus: F'	58.681
P Plane 1: P	5.953	P Plane 2: P'	-6.542
Nodal Point: N = F-f'	5.953	Nodal Point: N' = F'-f	-6.542
Entrance Pupil	0.000	Exit Pupil	-13.093
First - Last surf	18.500	First - image surf	77.181
Object height	----	Image height	-2.717
Lagrange Invariant	0.500		

Figure 7. Compound Optical System Paraxial Values

3.5 Triple Compounding

To optimize the system, several options were considered. A triple compounding system was proposed.

The main advantage of adding a lens and having a triple compounding system is the added lens power. The additional lens can refract the light further and can create different focus. Therefore, shortening the BFL while also increasing the maximum possible magnification. This also allows for the system to focus on a smaller area.

Another advantage of adding a lens is the added versatility of the system. This system could potentially be re-focused by rearranging the distances between the lenses.

Lastly, the addition of another lens further reduces the effects of achromatic aberration.

To determine the BFL of a system of more than one lens the lens equation must be applied to each optical element of the system [9]. These calculations must be iterated using elements of different f. It was calculated before that an optimal BFL of 64.5 mm is desired to have h_o of 25 km. Therefore, only combinations of lenses of this type are to be considered. Calculations were conducted as seen below:

1. The first lens equation is the following:

$$\frac{1}{f_1} = \frac{1}{d_{o1}} + \frac{1}{d_{i1}} \tag{6}$$

Here f_1 =175mm, $d_{o1} = \infty$. Since the object is assumed to be located at infinity, then $d_{i1} = f_1 = 175mm$.

2. The second lens equation is the following:

$$\frac{1}{f_2} = \frac{1}{d_{o2}} + \frac{1}{d_{i2}} \tag{7}$$

Here $f_2 = -100mm$, $d_{o2} = d - d_{i1}$, where $d = 1mm$ and is the distance between the first and second lenses. Therefore, $d_{o2} = -174mm$. Solving for d_{i2}, $d_{i2} = -235.1mm$ it is negative; therefore the image here is upside down and real.

3. The third lens equation is the following:

$$\frac{1}{f_3} = \frac{1}{d_{o3}} + \frac{1}{d_{i3}} \tag{8}$$

Here $f_3 = 50mm$, $d_{o3} = d - d_{i2} = 1mm + (-235.1)mm = 236.1mm$, solving for d_{i3}, $d_{i3} = 63.43mm$.

The total magnification (M_t) can be calculated in the same manner by applying the magnification equation for each optical component. The product of $M_1, M_2,$ and M_3 gives the total magnification. For this system, $M_t = -1.06 \times 10^{-6}$ this is an improvement of 36.3% compared to the single lens optical system.

Table 2. Optimal Lens Choices for a Compound

d_{i1}(mm)	175.0
d_{o1}(mm)	6.00E+08
f_1(mm)	175.0
d_{i2}(mm)	-235.1
d_{o2}(mm)	-174.0
f_2(mm)	-100.0
d_{i3}(mm)	63.43
d_{o3}(mm)	236.1
h_i(mm)	-2.647
M_t	-1.06E-7

The overall length of the system is 80.5mm this is a 47.2 % decrease in the overall length of the system compared to the one used for the ROARSAT. Also by adding the two lenses, the magnification has been improved by 36.3%. This means that this system will be able to zoom in and focus on an area with a height of 10.6 km. This system was chosen because of the great performance characteristics and the fact that this system can fit inside the 1U platform.

The design of this system as seen in Figure 8 features a fiberglass tube with an inner diameter of 25mm, and an outer diameter of 26mm it features three 1mm ×1mm and one 1mm ×2mm 41 inserts to fix the lenses in place. It also has the back sealed with a small opening that is the size of the desired image. This is done so that no unwanted light can be captured by the sensor.

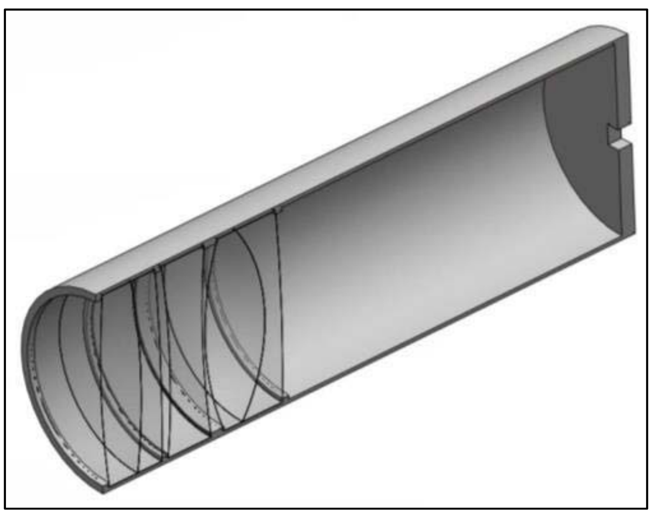


Figure 8. Section View of Triple Compound Optical System

The material used for this system is fiberglass this was picked because it is a cheap light-weight option that can protect the lenses. The interior of the tube is coated with a special anti-reflective paint that reduces the effects of stray light within the tube, therefore improving image quality.

3.6 Triple Compounding System Simulation

A simulation was run again on WinLens3D Basic to have a basis of comparison to the theoretical values. The three lenses with the predetermined f values were modeled within the software and arranged according to the design. Figure 9a, Figure 9b, and Figure 9c show the parameters of each lens that were modeled after commercially available lenses. Figure 10 and Figure 11 show the paraxial graph of the system and the paraxial values of the system respectively.

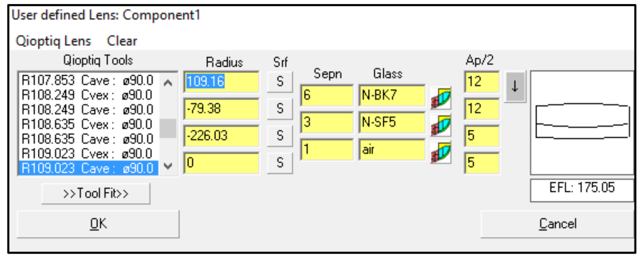


Figure 9a. Lens 1 Parameters

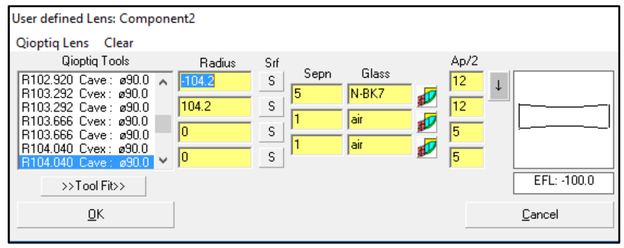


Figure 9b. Lens 2 Parameters

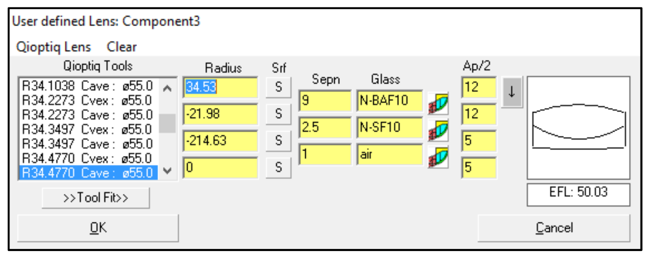


Figure 9c. Lens 3 Parameters

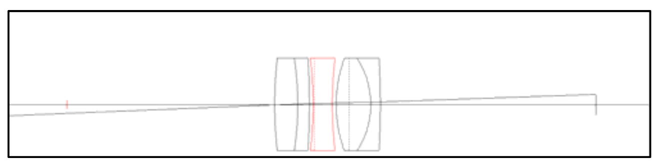
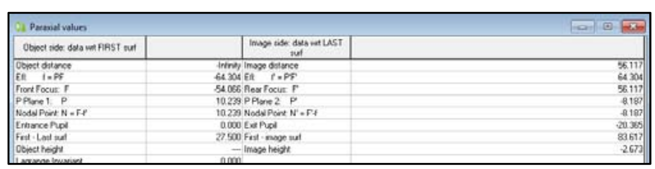


Figure 10. Triple Compounding Paraxial Simulation



Object side		Image side	
Object distance	-Infinity	Image distance	56.117
Efl: f = PF	-64.304	Efl: f' = P'F'	64.304
Front Focus: F	-54.066	Rear Focus: F'	56.117
P Plane 1: P	10.239	P Plane 2: P'	-8.187
Nodal Point: N = F-f'	10.239	Nodal Point: N' = F'-f	-8.187
Entrance Pupil	0.000	Exit Pupil	-20.365
First - Last surf	27.500	First - image surf	83.617
Object height	---	Image height	-2.673
Lagrange Invariant	0.000		

Figure 11. Triple Compounding Simulation Paraxial Values

4. CONSTRUCTION AND TESTING

4.1 Triple Compounding Construction

The optical system was manufactured manually because refractive systems have lower tolerances when it comes to lens alignment. The manufacturing process included several steps. First, a polyurethane cylindrical mod of a diameter of 25 mm and a length of 100mm was formed by sanding. Then two layers of fiberglass cloth were wrapped around the mold, bonded and hardened with a mixture of fiberglass resin, resin hardener, and acetone. Once the fiberglass was hardened the mold was removed, and all the surfaces of the optical tube were sanded to have a smooth finish. Then the tube was cut into its designed dimensions with a bandsaw. Another cut was made longitudinally to fit the lenses. The lens fittings were molded from excess material and bonded to the inner surface of the tube using an aerospace certified epoxy compound. Then the whole tube was painted with a light absorbing optical coating This coating is manufactured by Albrecht and was highly recommended by experienced telescope manufacturer Gerd Neumann Jr [11]. Finally, the lenses were fitted, and the tube was closed and clamped with two light-weight aluminum clamps.

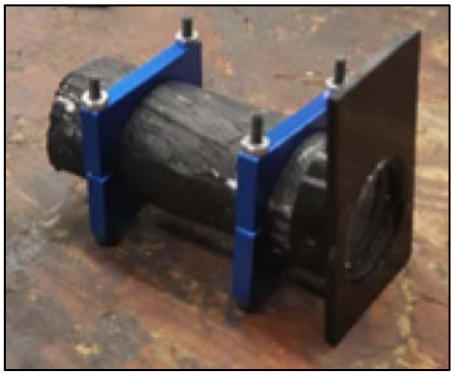


Figure 12. Final Optical System Assembly

4.2 Testing

The system was tested to validate the theoretical and simulation values of the design. Since it would be unfeasible to take an image of 25 km from 600 km away at the earth's surface, the test setup was scaled down. Instead, a 25 cm object height was to be photographed from 6 m.

To accomplish this, the TTL camera was fixed behind the optical tube and was plugged into a Beagle Bone Black (BBB). The BBB was operated by a program developed by the author (Dr. Pradeep Shinde) that prompted the camera to shoot a picture every 10s.

The result of this test gave an image height of 25 cm as designed. Due to the low quality of the camera, the image quality is not optimal; therefore, a higher quality camera is proposed for future testing.

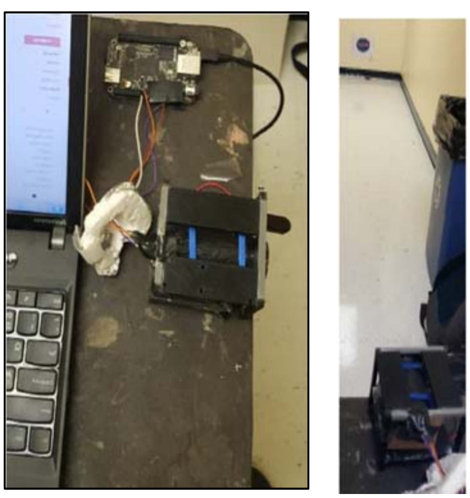


Figure 13. Optical System Setup

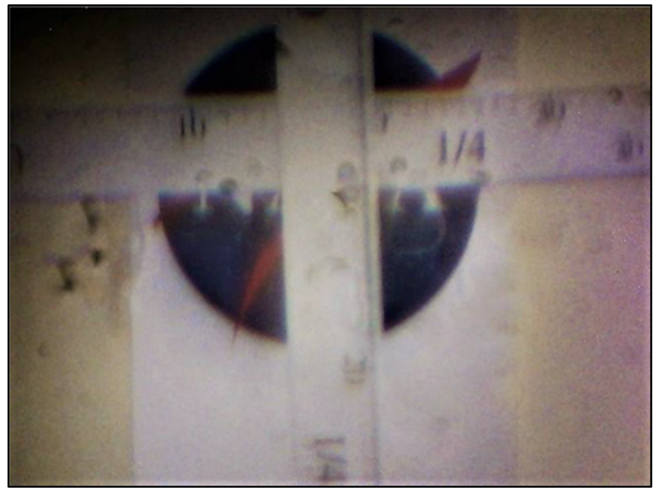


Figure 14. Optical System Test Image

The overall size of the system not only assures that it will fit in the satellite, but it is imperative to the overall quality of the image that is to be processed by the camera. As it was found in testing a slight deviation on the placement of the camera behind the tube would have significant deterioration of image quality. Therefore, it is imperative that the camera is placed right at the focal plane of the system.

5. DISCUSSION

It is important to notice that all previous calculations were made assuming the lenses are thin. However, the achromatic lenses are rather thick because they combine two different lenses. The thin lens estimation can be used for the first two lenses but the third lens has a thickness of 13.5mm; thus, the assumption is no longer valid. This is demonstrated with a simulation made with WinLens3D Basic. The paraxial results for this simulation are shown in Fig. 11. It clearly shows that the image distance is measured from the last surface, or be it the surface closest to the sensor, but this is not the BFL of the system. The BFL should be measured from the last lenses principal plane [10]. For a thin lens these would be one and the same, but for the 50mm focal length, the principal plane is located $9.351mm$ from the last surface. Therefore, the sensor can be located at a shorter distance from the last surface making the entire system smaller.

The total cost of the optical system was of $275.25 the price of the camera was not included because it was provided by the NEE club at FIU. Because a very light composite material was used for the optical tube, the total weight of the system was reduced to 67.4g as it can be seen Table 3.

Table 3. Cost and Weight Estimate

Component	Weight	Length	Diameter	Cost
175mm *f* AD Lens	15 g	9.0 mm	25 mm	$89
-100mm *f* Lens	8g	6.4 mm	25 mm	$39
50mm *f* AD Lens	15.9g	11.5mm	25mm	$89
2 x Aluminum Clamp	19g	N/A	30mm	$7.66
Optical Paint	N/A	N/A	N/A	$21.11
Optical Tube	9.5g	80.5mm	30mm	$29.48
Total	67.4g			$275.25

6. CONCLUSION

A small light weight cost effective optical system has been designed, manufactured and tested. The system can focus on to an area of at least 25km. The overall size of the system was reduced from the ROARSAT design by 47.2% without sacrificing functionality. This was accomplished by compounding 3 lenses, two biconvex achromatic doublets, and one biconcave lens. The combined lens power not only reduced the size of the system but also increased its magnification by 36.3%.

The system was manufactured and tested with satisfactory results. The overall fiberglass optical tube though very lightweight will have to be further tested for its integrity under critical conditions.

A vibration test is also recommended in the future to verify that the alignment of the lenses does not become compromised during launching. Furthermore, several image quality tests must be conducted to assure maximum performance of the system.

7. ACKNOWLEDGMENTS

The development of NEESAT comes as a direct result of the work of the ROARSAT team. Therefore, the authors acknowledge the support guidance of the members of this team and recognize their achievements as first runners up for the FUNSAT 2014-16 competition organized by NASA's Florida Space Grant Consortium (FSGC). The authors also acknowledge the immense support provided by the Department of Mechanical and Materials Engineering (MME) at Florida International University (FIU). The authors finally wish to extend their gratitude toward members of the Near Earth Explorer (NEE) Student Club at FIU for helping with the development of the NEESAT optical system and for continuing its testing and optimization.

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