Design trade-off of a high resolution telescope for a remote sensing satellite

By

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Abstract:

In this paper several optical configurations for an orbiting high-resolution panchromatic push-broom camera are presented. The geometric design aspects for different optical sensor systems are discussed. Several optical telescope configurations emphasizing the challenges associated with high resolution imaging are studied. Different case studies and the result of a trade-off analysis, considering not only optical performance but also other aspects such as cost, volume and complexity are presented.

Keywords:

Remote sensing telescope, telescope design, telescope design trade-offs.

1. Introduction:

Getting a high resolution images from space in simple, low cost way without affecting the optical performance of the system is always the main challenge in the field of satellite telescope design [1, 2]. Currently, push-broom imaging technique is one of the best panchromatic scanners for high resolution space imagers [1, 3-6].

The main mission of the space bus determines the overall design strategy and considered the main driving force for optimization and trade-off analysis. Typically, the mission aspects determine the design requirements of both sensor and optics which in turn specify the design aspects of these subsystems.

For the purposes of telescope design, both sensor and optics subsystems are separately sub-divided into smaller sub-systems. Many researchers studied each sub-system in separate such as in [3-5, 7-11] and [1, 7, 12-16].

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In [3- 5, 7-11], research is mainly focused on the design of telescope sensors and their optimization methods from the points of view of resolution, pixel size, number of active pixels per line, signal integration technique, detector type, and detector performance. Studying and analyzing these researches we can conclude that a 1-D arrays of CCD detectors with smaller pixel size to allow high ground resolution, large pixel number to allow a large field of view (FOV) without affecting size, mass and volume and based on time delay integration (TDI) is highly recommended for remote sensing compared with 2-D arrays, this leads to larger field of view, and finally allows much greater scanning speeds especially in dark conditions compared with conventional linear sensors without TDI.

In [1, 7, 12-16], researchers focused on the optical system design techniques, approaches and optimization methods. From these trials we concluded that mirrors based techniques are more suitable for large optical systems than refractive lenses based techniques, since the later suffers from different performance degradation effects such as aberrations, larger size, mass and higher cost.

We also concluded that different design approaches such as two, three and four mirrors telescope designs with and without correcting optical elements are possible. However, three-mirror anastigmatic (TMA) configuration showed a suitable image quality, it is rarely used in practice because of the difficulties in its manufacturing and aligning. Also, changing mirrors type and their conic coefficients greatly affects the overall telescope performance; such as in Cassegrain and Ritchey-Chretien(R-C) telescopes.

It is also concluded that more mirrors with more location freedom, such as in Korsch telescope, leaded to better modulation transfer function (MTF) performance but other performance measures such as; design complexity, size, mass and cost are highly degraded.

Finally, two mirrors design with lens correctors can lead to superior performance capabilities with reasonable size, mass and cost

In this paper commercially available 1-D CCD array with TDI technique is employed. In section 2, general optical design parameters of space imaging systems are presented. The analytical design of 2-mirror system is presented in section 3. Design and simulation using ZEMAX software of different telescopes configurations are presented in section 4. Simulation results and analysis depending on the mission requirements are discussed in section 5. Trade-off studies for the selection of the best compromise solution are discussed in section 6. Finally; section 7 presents a conclusion and exclusive summary.

2. General space imaging system optical design parameters:

The general imaging system design parameters including the optics focal length (f), entrance aperture diameter (D), focal number (F/#), instantaneous field of view (IFOV), field of view (FOV) and swath width (SW) are mainly depend on other parameters such as ground pixel size (GRD), satellite orbit altitude (H) and the pixel size (x) as shown in Fig. (1) [3-5].All the design parameters can be analytically derived using Equations (1-6).
In which, \( \lambda \) is the operating wavelength and Q is the imaging quality factor.

\[
F/\# = \frac{f}{D}
\]

(3)

\[
IFOV = 2 \cdot \tan^{-1} \left( \frac{GRD}{2H} \right)
\]

(4)

\[
FOV = 2 \cdot \tan^{-1} \left( \frac{L}{2f} \right)
\]

(5)

In which, \( L = n \cdot x \), L is the active line of detectors, \( n \) is number of active pixels.

\[
SW = H \cdot \frac{L}{f}
\]

(6)

3. The analytical design of 2-mirror telescope:

The design parameters of such system are radius of curvature of primary mirror (\( R_1 \)), radius of curvature of secondary mirror (\( R_2 \)), distance from primary to secondary mirror (\( d \)) and back focal
distance (b). The parameters are in direct relation with a set of normalized parameters such as obscuration ratio \( k \), ratio of mirror radii of curvature \( \rho \), transverse magnification of secondary \( m \) which defined as given in Equations (7-9) [12, 14].

\[
k = \frac{y_2}{y_1} \quad (7)
\]

In which, \( y_1 \) and \( y_2 \) are the marginal rays heights of the primary and secondary mirrors, respectively.

\[
m = -\frac{s_2'}{s_2} = \frac{f}{f_1} \quad (8)
\]

In which, \( s_2 \) is object distance of the intermediate object, \( s_2' \) is image distance of the intermediate object and \( f_1 \) is focal length of the first mirror.

\[
\rho = \frac{R_2}{R_1} \quad (9)
\]

Using the schematic geometry illustrated in Fig.(2), Equation (10) is derived and given by

\[
\frac{1}{s_2} + \frac{1}{s_2'} = \frac{2}{R_2} \quad (10)
\]

Equations (8) can be represented by normalized parameters; by the aid of Equations (8-10) and the derived relation \( s_2 = \frac{kR_1}{2} \) (using the schematic geometry illustrated in Fig. (2), and given by

\[
m = \frac{\rho}{\rho - k} \quad (11)
\]

![Fig. (2): Schematic diagram of two mirror reflecting telescopes](image)
In this section, it is required to determine the best optical configuration that fulfills the requirements of a real push-broom panchromatic scanner given in Table (1). Studying this case, we found that the best performing commercial detector for this system is the Fairchild CCD5061 with a pixel size, $x=8.75 \, \mu m$, number of active pixels per line, $n=6144$ and uses 128 TDI stages.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Spectral bandwidth (panchromatic) & 400-700 nm \\
\hline
H & 460km \\
\hline
GRD & 1.6m \\
\hline
(MTF) of the optics (at Nyquist frequency) & $\geq 30\%$ \\
\hline
\end{tabular}
\caption{Requirements of the push-broom panchromatic scanner}
\end{table}

In order to determine the best configuration we studied different configurations, for this purpose there are some space imaging system parameters have to be determined analytically. Equations (1-6) are solved using the system requirements presented in Table (1) and leaded to the following telescope design parameters shown in Table (2).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
f & 2.5m \\
\hline
D & 0.42m \\
\hline
F/number(system) & $\approx 6$ \\
\hline
IFOV & $\pm 1.74 \, \text{rad}$ \\
\hline
FOV & $\pm 0.6 \text{deg}$ \\
\hline
SW & $\approx 9900 \, \text{m}$ \\
\hline
\end{tabular}
\caption{Calculated telescope design parameters}
\end{table}

In the rest of this section we will try to study different telescope configurations to find the best configuration that fulfills the two main performance measures to assess the resolution of the telescope which are the MTF and the spot diagrams. The MTF is a quantitative measure of image quality that describes the ability of an optical system to transfer an object contrast to its image.
An MTF relates the working spatial frequency of the optics, in units of line pair cycles per millimeter, to the percentage of the contrast measured from the original image [1]. The MTF at Nyquist frequency, $f_{Ny}$, is given by:

$$f_{Ny} = \frac{1}{2x}$$  \hspace{1cm} (14)

Using the selected CCD sensor parameters (Fairchild CCD5061 with a pixel size of 8.75 m and substitute in Equation (11), the Nyquist frequency, $f_{Ny} \approx 57.14$ cycles/mm.

As we discussed in section 1, the most effective optical configurations are; Cassegrain, Ritchey-Chretien, korsch and Ritchey-Chretien with correction lenses. All the configurations are studied analytically, designed, implemented and their performances are analyzed using ZEMAX® software package [17] and presented in the rest of this section.

1) Cassegrain telescope design and simulation using ZEMAX

The Cassegrain telescope distinguished with its comparatively simple, cheap, and easy to design. It has two mirrors, the first is parabolic mirror (M1) with conic coefficient $k_1 = -1$ and the second (M2) is hyperbolic mirror with conic coefficient $k_2$. Using the calculated telescope parameters in Table (2), suitable values for F/number of 1.64 for the first mirror and obscuration ratio, $k \approx 0.238$, then substituting them in Equations (7-11) for two mirror telescope, we calculated all the telescope parameters and the results are shown in Table (3). The next step was the design optimization for $R_2$, $k_2$ and the distance between M2 and the focal plane (FP) using ZEMAX and results are shown in Table (4). Using the calculated design parameters and the results of optimization in ZEMAX, the simulation results of Cassegrain telescope is illustrated in Fig. (3).

<table>
<thead>
<tr>
<th>Table (3): Calculated two mirrors telescope design parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_2$</td>
</tr>
<tr>
<td>$m$</td>
</tr>
<tr>
<td>$p$</td>
</tr>
<tr>
<td>$R_2$</td>
</tr>
<tr>
<td>$d$</td>
</tr>
<tr>
<td>$b$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table (4): The Cassegrain telescope layout using ZEMAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Type</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>OBJ</td>
</tr>
<tr>
<td>1*</td>
</tr>
<tr>
<td>2MT*</td>
</tr>
<tr>
<td>3*</td>
</tr>
<tr>
<td>1M</td>
</tr>
</tbody>
</table>
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Fig. (3): A Zemax simulation of the Cassegrain telescope

2) **Ritchey-Chrétien telescope (R-C) design and simulation using ZEMAX**

In order to further reduce the off axis aberration and get better image quality, we studied the optical configuration of the Ritchey-Chrétien telescope. It employs two hyperbolic mirrors with conic coefficients \( k_1 \) and \( k_2 \). Using the same parameters in Table (3), and the results of optimization for \( R_2 \), distance between M2 and FP, \( k_1 \) and \( k_2 \). The R-C telescope layout using ZEMAX is shown in Table (5) and its schematic design is illustrated in Fig.(4).

*Table (5) : The R-C telescope layout using ZEMAX*

<table>
<thead>
<tr>
<th>Surf. Type</th>
<th>Comment</th>
<th>Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Semi-Diameter</th>
<th>Conic</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° Standard</td>
<td>Infinity</td>
<td>Infinity</td>
<td></td>
<td>Infinity</td>
<td></td>
<td>0.00000</td>
</tr>
<tr>
<td>1° Standard</td>
<td>-45.38332</td>
<td>52.571400</td>
<td>0.000000</td>
<td>0.000000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TO° Standard</td>
<td>-158.99066</td>
<td>-52.571400</td>
<td>52.986514</td>
<td>-1.958777</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0° Standard</td>
<td>-47.391500</td>
<td>50.572770</td>
<td>5.510059</td>
<td>-4.222499</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IRA Standard</td>
<td>Infinity</td>
<td></td>
<td>2.376520</td>
<td>0.000000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. (4): A Zemax simulation of the R-C telescope

After simulation we notice that the conic constant for the secondary mirror is more negative than for the Cassegrain. The total track of the R-C telescope is approximately the same as Cassegrain telescope.
3) **Korsch telescope design and simulation using ZEMAX**

Korsch telescope consists of four mirrors (three aspheric mirrors and one flat folding mirror). Increasing two optical elements (fold mirror and tertiary mirror) lead to better image quality due to more available degrees of freedom. Using the same parameters in table (3), and results of optimization of initial values for \( R_3 \), conic coefficient of third mirror \( k_3 \) and distance between \( M_2 \), third mirror \( M_3 \), fold mirror \( FM \) and FP, the proposed Korsch telescope layout using ZEMAX is shown in Table (6). Figure (5) illustrates the simulation results of the proposed Korsch telescope using ZEMAX software.

**Table (6): The Korsch telescope layout using ZEMAX**

<table>
<thead>
<tr>
<th>Surf. Type</th>
<th>Comment</th>
<th>Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Semi-Diameter</th>
<th>Conic</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Standard</td>
<td>Infinity</td>
<td>Infinity</td>
<td>Infinity</td>
<td>0.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>1°</td>
<td>Standard</td>
<td>-64.30000</td>
<td>62.57111</td>
<td>NIPDMS</td>
<td>21.05471</td>
<td>-0.981039</td>
</tr>
<tr>
<td>2°</td>
<td>Standard</td>
<td>-158.00000</td>
<td>-62.57111</td>
<td>NIPDMS</td>
<td>21.05471</td>
<td>-0.981039</td>
</tr>
<tr>
<td>3°</td>
<td>Standard</td>
<td>-64.30000</td>
<td>62.00000</td>
<td>NIPDMS</td>
<td>5.000000</td>
<td>-2.020219</td>
</tr>
<tr>
<td>4°</td>
<td>Standard</td>
<td>-56.00000</td>
<td>-23.00000</td>
<td>NIPDMS</td>
<td>5.250000</td>
<td>-0.645000</td>
</tr>
<tr>
<td>5° Correct Break</td>
<td>0.00000</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6°</td>
<td>Standard</td>
<td>Infinity</td>
<td>0.00000</td>
<td>NIPDMS</td>
<td>2.166000</td>
<td>0.000000</td>
</tr>
<tr>
<td>7° Correct Break</td>
<td>22.00000</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM</td>
<td>Standard</td>
<td>Infinity</td>
<td>0.000000</td>
<td>0.000000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. (5): A Zemax simulation of the Korsch telescope**

After simulation we notice that the conic constant for \( M_1 \) and \( M_3 \) is ellipse while \( M_2 \) is hyperbolic, and the total track of the Korsch telescope is larger than the Cassegrain telescope and the R-C telescope.

4) **R-C telescope with correction lenses design and simulation using ZEMAX**

To get a compact design with a good image quality, the Ritchey-Chrétien design was employed after compared with other two mirrors telescope designs based on its superior aberration correction capabilities, and to reduce the residual aberrations in FP we need more available degrees of freedom. Using the same parameters in table (3), the design is optimized by employing two lenses corrector elements \( L_1, L_2 \) and made of commercially available materials from the Schott catalog (BK7 and SF4 glasses) [18]. Then ZEMAX is used for the optimization of initial values for \( R_3, R_4, R_5, R_6, K_1, K_2 \),...
thickness of (L1, L2) and distance between M2, L1, L2 and FP. The proposed R-C telescope with correction lenses layout using ZEMAX is shown in Table (7). The complete R-C telescope with correction lenses design based on the results presented in Table (7) and using ZEMAX software is illustrated in Fig. (6).

Table (7): The R-C telescope with corrector lenses layout

| Surf Type | Thickness | Glass | Focal-Distance | Conic  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0° Standard</td>
<td>infinity</td>
<td>infinity</td>
<td>1.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>2° Standard</td>
<td>-45.93302</td>
<td>8.257120</td>
<td>1.000000</td>
<td>0.000000</td>
</tr>
<tr>
<td>3° Standard</td>
<td>-131.03800</td>
<td>-37.57116</td>
<td>MI1BD</td>
<td>1.057565</td>
</tr>
<tr>
<td>4° Standard</td>
<td>-45.63300</td>
<td>8.303100</td>
<td>MI1BD</td>
<td>5.603317</td>
</tr>
<tr>
<td>5° Standard</td>
<td>1.99861</td>
<td>0.23465</td>
<td>MI1BD</td>
<td>1.940324</td>
</tr>
<tr>
<td>6° Standard</td>
<td>1.24320</td>
<td>0.52000</td>
<td>MI1BD</td>
<td>1.709214</td>
</tr>
<tr>
<td>7° Standard</td>
<td>1.05530</td>
<td>0.39930</td>
<td>MI1BD</td>
<td>1.025564</td>
</tr>
<tr>
<td>8° Standard</td>
<td>4.413567</td>
<td>1.985534</td>
<td>MI1BD</td>
<td>2.247545</td>
</tr>
</tbody>
</table>

Fig. (6): A Zemax simulation of the R-C telescope with corrector lenses

After simulation we notice that the conic constant for M1 and M2 is not the same as in the R-C telescope without corrector lenses, and the total track of the R-C telescope with corrector lenses is nearly the same as in the Cassegrain telescope and the R-C telescope and not large as in the Korsch telescope.

5. Simulation results and analysis

1) Cassegrain telescope

According to the design and simulation of the Cassegrain telescope as discussed in section 4.(1). Figures (7) and (8) show spot diagrams and MTF for on axis and marginal FOV of Cassegrain telescope.
From Figures (7) and (8) we concluded that the total track of the system is 53.5725 cm, the on axis FOV has good image quality with zero RMS radius and MTF ($f_{Ny}$) value > 70%, but off axis marginal FOV suffer from coma aberration with RMS radius value of 142 microns which is much larger than the required pixel size, and its MTF ($f_{Ny}$) value <0.05%. So Cassegrain telescope has the ability to correct only spherical aberration.

2) **Ritchey-Chrétien telescope (R-C)**

According to design and simulation of the R-C telescope as discussed in section 4.(2). Figures (9) and (10) show spot diagrams and MTF for on axis and marginal FOV of R-C telescope, while Fig. (11) shows the tangential (T) and sagittal (S) surfaces.
From Figures (9) and (10) we concluded that the total track of the system is 53.5728 cm, the on axis FOV has good image quality with RMS radius = 0.34 microns and MTF (fNy) value > 70%, but off axis marginal FOV suffer from astigmatism with RMS radius value of 125.4 microns which is much larger than the required pixel size, and its MTF (fNy) value <0.006%. So R-C telescope has the ability to correct both coma and spherical aberration but suffers from astigmatism and the curvature of image surface. We also concluded from Fig. (11) that R-C telescope gives approximately 0.1 cm difference between tangential and sagittal surfaces which degrades the overall performance of this system.

3) Korsch telescope

According to the design and simulation of the Korsch telescope as discussed in section 4.(3), ZEMAX is used to predict spot diagrams and MTF for on axis and marginal FOV of Korsch telescope as shown in Figures (12) and (13). Also, it is used to show the coincidence between T and S surfaces and how Korsch telescope overcome the residual aberrations as shown in Fig. (14).
From Figures (12) and (13) we concluded that the total track of the system is 82 cm, the on axis FOV has good image quality with RMS radius = 0.761 microns which is inside the pixel size and its MTF \((f_{Ny})\) value \(\approx 0.4\), where the off axis marginal FOV has good image quality with RMS radius = 2.694 microns which is also inside the pixel size and its MTF \((f_{Ny})\) value \(\approx 0.39\). Therefore, we can conclude that Korsch telescope has the ability to solve the aberration problems exist in Cassegrain telescope and R-C telescope. We also concluded that this telescope configuration and design leaded to a complete coincidence between T and S surfaces which make it suitable for the current requirements. After studying the Korsch telescope we noticed that this telescope has a very good off axis image quality but
the longitudinal size of the system is much larger than in the previous cases which increase mass, volume and cost.

4) **R-C telescope with corrector lenses**

According to the design and simulation of the R-C telescope with corrector lenses as discussed in section 4.(4), and using ZEMAX, Figures (15) and (16) show spot diagrams and MTF for on axis and marginal FOV of this telescope. While Fig. (17) shows the approximate coincidence between T and S surfaces at marginal FOV.

![Fig. (15): R-C telescope with corrector lenses spot diagram](image1)

![Fig. (16): R-C telescope with corrector lenses MTF](image2)

![Fig. (17): R-C telescope with corrector lenses tangential and sagittal surfaces](image3)
From these figures we concluded that the total track of the system is 60.2 cm, the on axis FOV has good image quality with RMS radius = 0.406 microns which is inside the pixel size and its MTF ($f_{Ny}$) value > 0.7, where the off axis marginal FOV has good image quality with RMS radius = 1.048 microns which is also inside the pixel size and its MTF ($f_{Ny}$) value > 0.7. So we can conclude that the telescope has the ability to solve the aberration problems exist in Cassegrain telescope and R-C telescope but it has a large value of MTF ($f_{Ny}$).

6. Trade-off study for the selection of the best compromise solution

The driving parameters which used for the trade-off in order to select the best compromise solution are image quality (MTF at the Nyquist frequency and the spot diagrams), complexity (number of optical surfaces), the longitudinal and transverse size of the telescope, mass (volume of the optics) and cost (shape and size of the surface).

Taking all together, the design results presented in section 4 and the simulation results presented in section 5, these parameters are summarized in Table (8) for the studied four optical configurations.

<table>
<thead>
<tr>
<th></th>
<th>Cassegrain</th>
<th>R-C</th>
<th>Korsch</th>
<th>R-C with correctors</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTF($f_{Ny}$)</td>
<td>&lt;30%</td>
<td>&lt;30%</td>
<td>&gt;30%</td>
<td>&gt;30%</td>
</tr>
<tr>
<td>Spot diagram</td>
<td>out pixel</td>
<td>out pixel</td>
<td>inside pixel</td>
<td>inside pixel</td>
</tr>
<tr>
<td>Complexity</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Size</td>
<td>medium</td>
<td>medium</td>
<td>large</td>
<td>medium</td>
</tr>
<tr>
<td>Mass</td>
<td>small</td>
<td>small</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>Cost</td>
<td>low</td>
<td>low</td>
<td>large</td>
<td>medium</td>
</tr>
</tbody>
</table>

According to Table (8), Cassegrain telescope and R-C telescope are very suitable from the point of view of complexity, size, mass and cost but unsuitable from image quality point of view. Korsch telescope is very suitable from image quality point of view but has more mass, size, complexity and cost. Finally, R-C telescope with corrector lenses showed very suitable image quality, size and has an acceptable increase in mass and cost but it is unsuitable from the complexity point of view. Therefore, we can conclude that R-C telescope with corrector lenses is the optimal configuration for image quality, complexity, size, mass and cost.

7. Conclusion

In this paper, the design, implementation and analysis of four different telescope designs for remote sensing satellite are studied using ZEMAX software package. Optimization of each design was also performed using the same package. Trade-off study was performed to determine the optimum telescope configuration. We conclude that the best compromise optical configuration is R-C telescope with corrector lenses. Korsch telescope is considered a good optical configuration except its long size with respect to others. Finally both Cassegrain and R-C telescopes need corrector lenses to get high image quality that fulfill the requirements.
References: