Minimum Entropy for the Space Solar Telescope Automatic Focus

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ABSTRACT

The novel remote sensor of the Space Solar Telescope (SST) is scheduled for launch in 2008. It will be uniquely designed to be the world’s first facility capable of observing with \( \gamma = 0.1 \) spatial resolution in vector magnetograms in the photosphere and the chromosphere, and 0.5” in soft X-rays. The high spatial resolution makes the on-orbit automatic focus (AF) the key technique to catch images. The paper brings forward a new method of the minimum entropy (ME) criterion for the astro-observation. Furthermore, we have applied such technology to the on-orbit AF of SST. The emulational program calculated the image entropies of different off-focus states. Data indicate that the minimum image entropy is corresponding to the optimal image plane; the ME criterion is more suitable for the heavenly bodies of low contrast and the focusing precision is 0.01 mm (\( \delta = 0.01 \)mm).

Keywords: automatic focus, minimum entropy, imaging processing, Space Solar Telescope, remote sensor, astronomy

1. INTRODUCTION

The SST is equipped with a main optical telescope of 1 m aperture size. It is co-developed by the China Academy of Space and Technology, the National Astronomical Observatories, Chinese Academy of Sciences. The general scientific objective of SST is proposed as follows: to achieve a breakthrough advance in solar physics through coordinated, wide spectral coverage, highly resolving and continuously temporal evolutive observations of transient and steady states in solar hydrodynamic and magnetohydrodynamic processes. The SST has been equipped with the most advanced Two Dimensional Real-time Polarizing Spectrograph, the advanced attitude control system and high-precision correlation tracker. It will be the first remote sensor to obtain the vector magnetograms of \( \gamma = 0.1 \) spatial resolution, which is much less than the minimum scale 0.2” of the elementary flux tubes predicted by the solar physical scientists. The high spatial resolution, the complex launching condition and the dynamic space on-orbit environment make the on-orbit AF one of the key techniques.

Following the progresses of computer, the optical technology, the digital image processing technology, the image plane technology and the space exploration, the on-orbit AF has developed rapidly. The definition of AF is: the image plane accepts the objective information when the payload of satellite is running in orbit, calculates and balances the related information; after the corresponding judgment, moves the focusing mechanism by the closed-loop automatic focus system until the object image just locate on the image receiving plane of the receiver. Because the SST is a large caliber remote sensing system for astro-observation of small aberration and ultimate diffraction, we just need to analyze the influence of off-focus at the axis direction and adjust the AF system to the on-focus station.

Virtually, the minimum entropy criterion for on-orbit automatic focus is the integrated application of digital image process, the statistic optics and the information theory. Now, it is still a new theory taking the minimum entropy as the criterion for the space remote sensors to judge whether the camera receiving plane locates at the focus plane or not. It is even more a new technology when it was applied on SST, which is the great landmark in the astronomy world.
2 PRINCIPLE OF THE AF TECHNOLOGY

2.1 THE REQUIREMENT OF ON-ORBIT AF

The operating environment of a satellite payload during launch and orbit insertion is obviously distinguished with that of the ground-based optical instrument, no matter what it is for astro-observation or just for earth remote sensing. When launched, a rocket has to bear the acceleration and the violent vibration, and a great pressure difference will appear between the inner payload cabin and its outer during the high-acceleration launching. The space environment is very extreme: heat from the satellite apparatus, the sun, the earth radiance and the earth sunlight reflection makes the inhomogeneous thermal distribution of the satellite, the payloads and apparatus; the pressure of space orbit greatly changes with the distance away from the earth; the radiation of high-energy particle flux and high-energy radial from the universal bodies in orbit. The random changes of temperature, pressure, vibration and other effects will distinctly causes the variances of radius of mirror curvature, the mirror shape, the optical interval, the reflective index of materials and other optical parameters. Then, the off-focus of optical system and degradation of the image quality at image plane will arise.

The astrophysical scientists observe the solar magnetic field and do theoretic research by the SST, their scientific objects have the characteristic of low-contrast. It needs more CCD integrated time to get images of high signal-to-noise. The movement of satellite could cause the image shift, the instability of satellite attitude could cause the wobble of the SST main optical axis, both of them will make the image blur at the CCD integrated time and debase the spatial resolution of the SST. As above, at the environment condition of vacuum, low-temperature and high-energy radiance, it is the key to ensure the optical image quality for the whole optical remote sensor.

At present, the main methods to resolve the on-orbit AF for remote camera include: taking into account the influence of space environment to image during optical design, presetting the focus plane, adding other reference light-resource at the system end or adding other image system for reference to gain the optimal image plane, and so on. But the on-orbit operating condition is very difficult to simulate, and the deformation of assemblies could not be validate at different operating conditions. So the method of presetting focus plane can’t uproot the off-focus; and on the other way, adding light-resource or reference image system does not meet the structural requirement and the lightening trend of modern remote camera. So, the on-orbit real time AF is of momentous current significance and important engineering signification.

2.2 THE TECHNOLOGY FOUNDATION OF ON-ORBIT AF

For the remote optical system, the object is generally conducted as the continuous distribution of lots of point source of the incoherent light, and optical system is a lowpass, the object image \( g(x, y) \) is the convolute of the input image \( f(x, y) \) and the system point spread function \( h(x, y) \):

\[
g(x, y) = f(x, y) * h(x, y)
\]

And the output image is the intensity superposition of the images of points at the input plane object, the intensity distribution is:

\[
|g(x, y)|^2 = \iint |f(x, y)|^2 |h(\xi - x, \eta - y)| \, dx \, dy
\]

If the image after the lens system locates on the ideal image plane, it is clear and has high contrast; but on the other way, if it does not, the facular will disperse and the image will be blur, namely off-focus. Take an example, the object and the image planes are supposed on both sides of the optical system, the coordinates of the objective plane and the image plane are expressed respectively by \( (x_o, y_o) \) and \( (x_i, y_i) \), the object distance is \( d_o \), the image distance is \( d_i \). \( p(x, y) \) is the pupil function. Then the pulse response \( h(x_o, y_o; x_i, y_i) \) is expressed as:
\[ h(x_i, y_i; x_o, y_o) \equiv \frac{1}{\lambda^2 d_o d_i} \int P(x, y) \exp\left[ \frac{k}{2} \left( \frac{1}{d_o} - \frac{1}{d_i} \right) \left( x^2 + y^2 \right) \right] \exp\left[ -jk \left( \frac{x_o - x_i}{d_o} + \frac{y_o - y_i}{d_i} \right) \right] dx dy \] (3)

\[ \delta = \frac{1}{d_o} - \frac{1}{d_i} f \] (4)

In which, \( \delta \) shows the state of off-focus, \( P(x, y) \) is the generalized pupil function\(^{14} \), \( P(x, y) = p(x, y) \exp[ jk w(x, y, 0) ] \). The aberration function, \( \exp[ jk w(x, y, 0) ] \), takes the aberration introduced by the off-focus into account. When \( \delta \neq 0 \), it is shown that the system is off focus. In essential, image can be regarded as the convolution of the pulse response of the optical system and the geometry image. The image is the flat distortion of object whose details have been attenuated.

2.3 The Histogram of Gray Image, the Concept of Image entropy and the Criterion of ME

The histogram of gray image states that \( p(i) \) is the relative frequency of pixel number at a certain gray scale \( i \) in the range of gray\(^{16} \). Figure 1 is the original image of rice.tif and Figure 2 is the histogram of gray image of the object image rice.tif. The image entropy\(^{16-17} \) \( H \) is expressed as:

\[ H = -\sum_i p(i) \log_{10} p(i) \] (5)

At the digital image processing, the image entropy method has been widely applied to identification of digital image, restoration of image, elimination of image noise and so on. In fact, applying entropy on digital image processing is one of the methods of statistics\(^8,18-19 \), and it also adapts a concept of Shannon in information science. As above, the paper has stretched the widely applications of the image entropy\(^{20} \). From some articles, we can find that, image entropy is more effective than other methods, which are regularly used in digital image processing. On image restoration\(^8,17 \), for example, if we use image entropy to process the weak target-to-background contrast object, the restored image and the object will be extremely alike. Even though on the part, on which optical intensity varies so extremely, this method was obviously suitable than others. So, the image entropy is obviously very fit for astronomical scenery that has the characters (such as view of sharp pulses on dark background, low albedo and black background and so on). We consider that entropy criterion is especially fit for SST, because the object of astro-observation has the above typical character of low albedo and the Sun (the science object of SST) has the same character.

If the optical system is under the state of on-focus, images will be very clear and its high frequency part will strengthen\(^{21} \). On the other word, if it is under the state of off-focus, images will get blurry, the specific portion of the
image will be reduced. On statistics, the more the off-focus, the more the disorder, and the larger the entropy value. So, it takes the minimum entropy as the criterion of on-focus.

3. RESULTS AND DISCUSSION

Because the bulk test for SST has not been carried out, it can’t directly joint-debug and test the AF system. We have developed an integrated test system special for the SST’s ground image experiment, the simulation test system is a full-scale model without aberration on optical axis, its pupil is $\Phi 80 \text{mm}$ and $F^* = 12.5$. The simulation test system has provided a credible experiment and test condition for the AF test, what we just need to do is placing the closed-loop AF system into it.

Process of the simulation test are following: firstly, takes a common image in astro-observation, granulation.tif, as the original object image, passes through the simulation test system, it finally locates on different off-focus planes; secondly, writes matlab program, reads in the image files of different off-focus planes, calculates the entropies for images and compares them; lastly, finds out the minimum from these image entropies and makes sure whether the minimum corresponds to the optimal focus plane or not. Figure 3 and figure 4 show the image of granulation.tif and the histogram of original object image; Figure 5 shows the image, which has passed through the optical test system and the image is one of the images within the focal depth, figure 6 shows the related histogram. Figure 7 and figure 8 show the image out of the range of focus depth and its histogram.

Table 1 is the calculated results of the image entropies at different image planes (include on-focus and off-focus) after the simulation test. Figure 9 shows the trend of image entropies at different image states.
Table 1  The Calculated Results of the Image Entropies at Different Image Planes

<table>
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<tr>
<th>Image planes(mm)</th>
<th>Image Entropies (H)</th>
<th>Image planes(mm)</th>
<th>Image Entropies (H)</th>
<th>Image planes(mm)</th>
<th>Image Entropies (H)</th>
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</table>

Fig.9 The Trend of Image Entropies at Different Image Planes

4. CONCLUSIONS

From the figures and table above, we can get conclusions as following:

a. The more blurred the image, the fainter the edge of object, and the high frequent part will weaken.

d. The more blurred the image, the more even the pixel numbers of gray scales of the corresponding histograms.

e. The larger the image off-focus, the larger the image entropy, so the minimum entropy can be taken as the criterion of on-focus.

f. The image entropy varies with the top focal length and has the minimum at the in-focus state.

g. It can be concluded that the image entropy reaches the minimum at the time of on-focus, and the focusing precision can be up to 0.01mm.

So, we can conclude: as the on-focus criterion, image entropy is a new algorithm; it had been approved by simulation and experiment. At the same time we have explained that the method of image entropy has meaning for the observation of the low contrast celestial bodies. Especially for SST, whose space image resolution will come up to 0.1”, the real closed-loop AF unit is absolutely necessarily. To take a clear image for any optical remote sensor, we should not only consider the parameters of optical remote sensor, the optical design, but also we should add the AF unit. Through the on-orbit AF system, we can solve the problem of blur image radically. So, on-orbit Auto-focus unit is the important part of the optical remote sensor.
The following task is that we should equip the ground image experiment system with the auto-focus unit. Further more, we should make an experiment on closed-loop focusing and analyze all kinds of data error from the experiment. On the premise of high focusing precision, we will devote ourselves to researching the repeatability and stability of the auto-focus system.

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