Ghost Busters: Subaru/HSC Ghost Analysis&Removal (2) Arc Ghosts

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Abstract

We have investigated the optical ghosts generated on the images of Hyper Suprime-Cam (HSC). In this presentation, we focus on the arc-shaped (or mustache-shaped) ghost which is located near the edge of the field of view of HSC. The standard ray tracing on HSC model can not predict this feature, however, we finally identified that the ghost is constructed by the ray which goes through the rim of the 3rd lens (G3) of the wide-field corrector. In order to hold G3 in ceramic lens holder, there is narrow unpainted flat glass surface at the rim of G3. This gap does not affect in small incident angle up to about 0.88 degree from optical axis. But, in the case of incident angle range 0.89-0.99 degree, a small amount of light can pass this gap and reach the detector surface. So if a bright star is located little bit apart from the field of view of HSC, the arc ghosts will appear. Now we understand the principle of constructing arc ghosts, we can predict their appearance, position, and size. We show how well the optics model including unpainted flat surface of G3 reproduces the position and the shape of the ghost. Image masking process will be introduced into the HSC pipeline as an optional function.

1. Introduction

Hyper Suprime-Cam (HSC) is a powerful CCD camera on the Subaru Telescope which covers the 1.5 degree diameter field of view. In early phase of HSC observation, we noticed that many arc-like ghosts appear near the edge of HSC field of view (see Fig 1 (left)). It was easy to find the source star of these ghost (Fig 1 (middle)), however, the mechanism for creating these ghosts can not be found for long time.

These arc ghosts have these properties: (1) field angle of source stars are distributed between 0.88 and 0.99 degrees, (2) larger field angle source star makes a ghost which is more distant from the optical axis, (3) all ghosts have central gap. Property (1) says there are some strict positional condition to make the ghost on the CCDs, property (2) suggests that there are even number reflections in light path of ghosts, and property (3) might be due to the central obstruction of the POPT2.

We finally found the mechanism and reproduce arc ghost well by the ray tracing (Fig1 (right)).

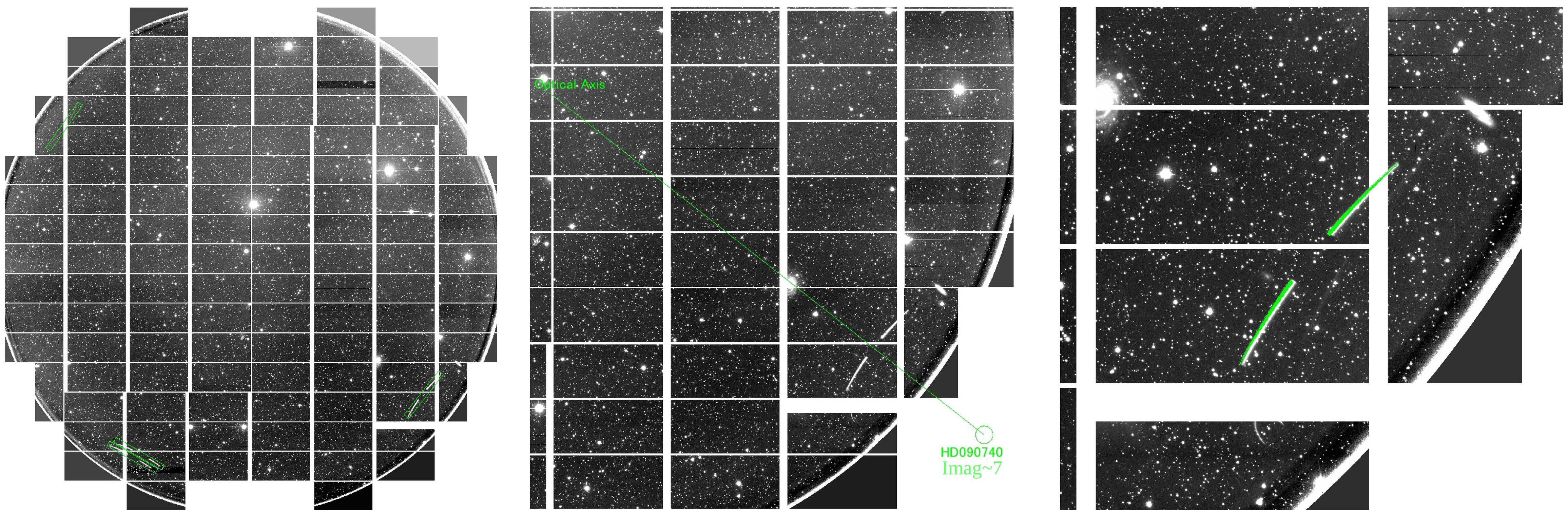

Fig.1: (Left): Arc ghost examples located near the edge of HSC FoV. (Middle): An arc ghost and corresponding (source) star. (Right): Ghost reproduced by ray tracing is overlayed as green circles.

2. Arc Ghosts

The rim of the HSC wide-field corrector (WFC) lenses are polished and unpainted in order to be held by the ceramic lens holders. In the case of the third lens of WFC (G3), it has relatively wide clear rim in its front side because of strong concave surface. The G3 retainer ring has a stop to hide the clear rim of G3 from incident light and the diameter of the stop is smaller than the inner edge of the G3 rim. However, the diameter of the stop is not sufficiently small.

In the case of large field angle, incident light has some positive radial component at the G3 retainer. So some potions of rays can reach the G3 clear rim (see Fig 2 left). These rays are not affected by the negative power of G3 front surface that refract rays toward outside of G4, and advance to G4, G5, … and finally the CCDs (see Fig 2 middle and right).

Since we don't have precise measurement of the radius and deviation from the circular form for the inner edge of G3R1 clear rim, there are some uncertainty in our simulation.

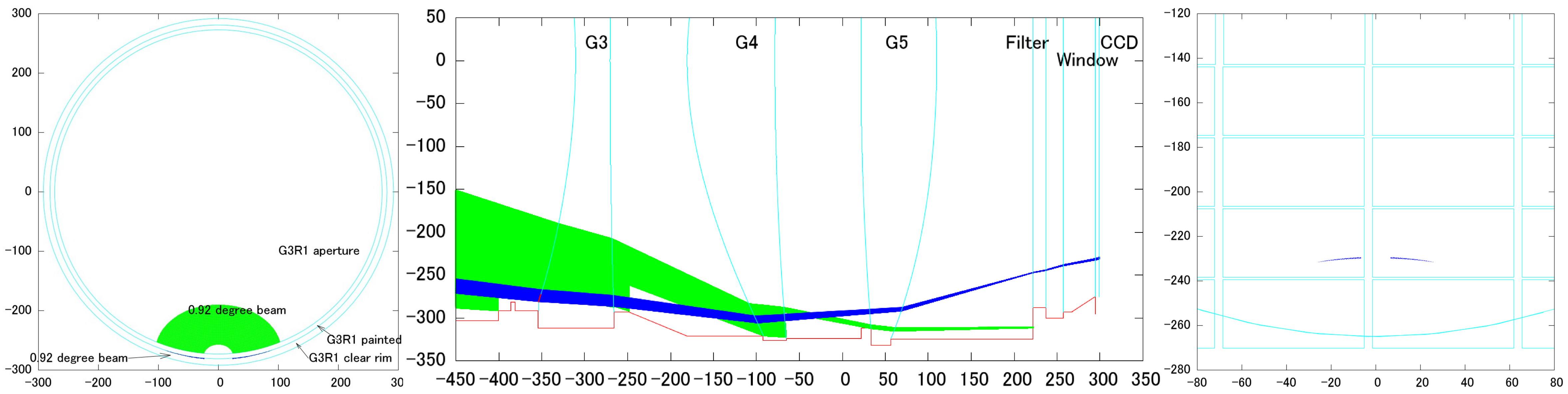

Fig. 2: Field angle 0.92 degree point source beam on the front surface of G3 lens(left), side view of the beam on the bisection of the optics(middle), and simulated image on the CCDs (right).

3. Removal Method

The method to remove the ghost is very simple as is described below.

Calculate the parameters (Arc center distance, arc radius, arc length, and gap length) of the ghost as a function of the field angle of the source star (θ) and central wavelength of a filter (λ) using the optics model.

1. For a certain exposure (visit), search candidate stars in a star catalog by criteria of a star located in a range from the optical axis of telescope.
2. Calculate θ and ghost image by using of pre-calculated parameters in order of the brightness of candidate stars.
   - Stop process if the ghost level becomes sufficiently low.
3. Mask the relevant pixels in the exposure according to the prediction.
4. Coadd masked exposures (Note that this method assumes that the dataset is composed of dithered exposures with appropriate intervals).

Fig 3-1 shows the predicted position and shape of the ghosts for HSC-i2. Note that these position and shape are depend on filters. Fig 3-2 and 3-3 show the parameters of arc ghost as a functions of θ.

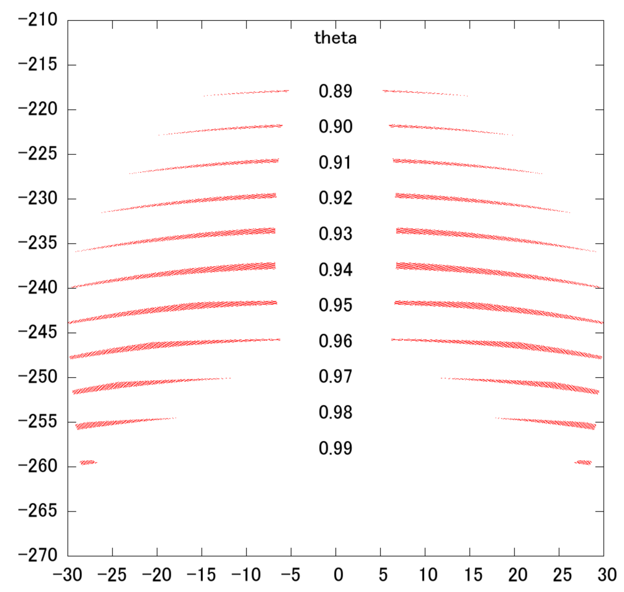

Fig. 3-1: The simulated shape of the arc ghosts as the function of θ for HSC-i2 filter. The obscuration of the prime focus structure is included in the calculation. Non-axisymmetric features (stacker of filter exchanger, spiders of telescope) are not included.

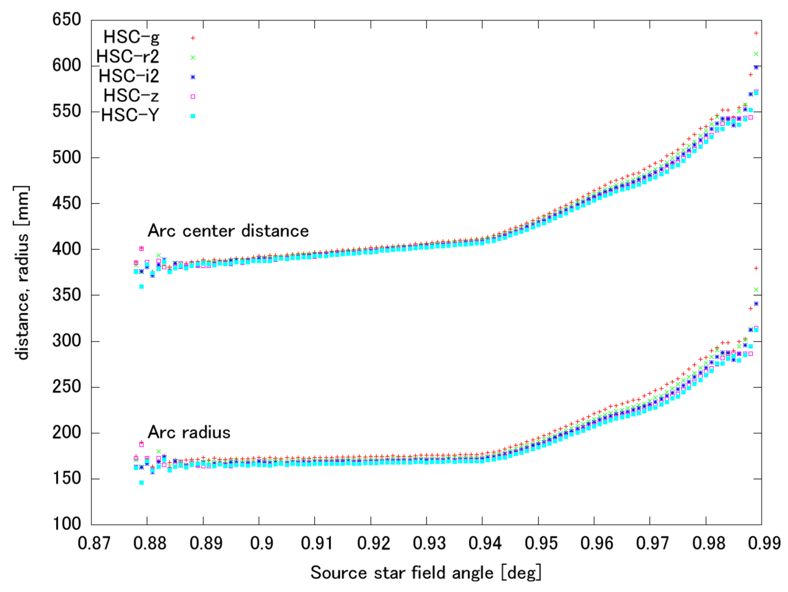

Fig. 3-2: The predicted arc center distance and arc radius of the ghost as functions of θ. Data in [0.88,0.94] range can be fitted well in a function $a+b/\lambda[um]+c*\theta[deg]$. Fitting results for the arc center distance and arc radius are: $c(\lambda,\theta)[mm]=-60.487+3.864/\lambda + 493.185*\theta$ and $r(\lambda,\theta)[mm]=+66.559+6.101/\lambda + 102.998*\theta$, respectively.

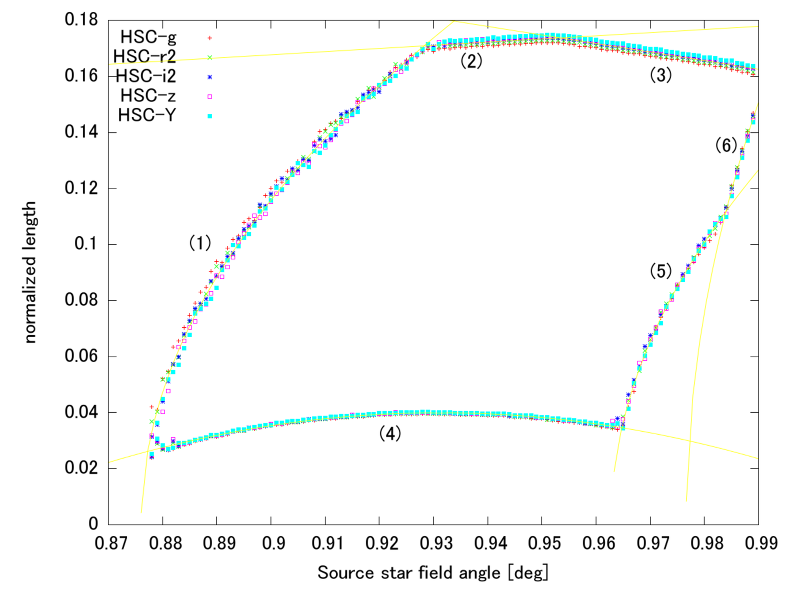

Fig. 3-3: The predicted size (arc length (1,2,3), gap length (4,5,6)) of ghost as a function of θ. Both length are normalized by corresponding arc radius. The data points are fitted with square root (1,5,6), linear (2,3), and quadratic (4) function. Wavelength dependency seems to be small. Fitting results are: $f1(\theta)=0.74774+0.87603*\mathrm{sqrt}(\theta)$, $f2(\theta)=0.066128+0.11285*\theta$, $f3(\theta)=0.46512-0.30564*\theta$, $f4(\theta)=0.039944-4.7459*(\theta-0.93117)**2$, $f5(\theta)=0.76672+0.96272*\mathrm{sqrt}(\theta)$, and $f6(\theta)=1.3041+0.97663*\mathrm{sqrt}(\theta)$.

4. Application to the Real Images

Fig. 4: Sample image of the arc ghost removal. Left panel shows arc-ghost removed image. Right one shows original image.
Ghost removed image is generated by clipped coadding of 5-dither raw imags in HSC-pipeline. The most significant arc ghost corresponds to HD135905(Rmag=7.4), the second one is created by HD135676(Rmag=8.1). The remaining arc ghost might relate to TYC-4186-347-1(Rmag=9.5).

5. Issues to be resolved

Typical width of arc ghosts are about 80pixels. The positional error of prediction is several tens of pixels. So now we are masking twice area of real ghost regions for a tolerance.

We should:

1. Introduce non-axisymmetric structure
   - Filter stacker of the filter exchanger
   - Telescope spiders
   - Alignment error of POPT2
   - Alignment error of HSC camera unit
   - Atmospheric dispersion compensator
2. Introduce astrometry and correct the telescope pointing
   - A few arcsec error between commanded and obtained position in HSC / Subaru telescope.
3. Introduce band width of filters
4. Introduce Fresnel diffraction
5. Improve star catalog
   - Especially in HSC-i2, HSC-z and HSC-Y filter, unexpected bright IR star and its ghost frequently appeared in a image.