AKARI OBSERVATION OF THE SUB-DEGREE SCALE FLUCTUATION OF THE NEAR-INFRARED BACKGROUND

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ABSTRACT

We report spatial fluctuation analysis of the sky brightness in the near-infrared from observations toward the north ecliptic pole (NEP) by the AKARI at 2.4 and 3.2 μm. As a follow-up study of our previous work on the Monitor field of AKARI, we used NEP deep survey data, which covered a circular area of about 0.4 square degrees, in order to extend fluctuation analysis at angular scales up to 1000′. We found residual fluctuation over the estimated shot noise at larger angles than the angular scale of the Monitor field. The excess fluctuation of the NEP deep field smoothly connects with that of the Monitor field at angular scales of a few hundred arcseconds and extends without any significant variation to larger angular scales up to 1000′. By comparing excess fluctuations at two wavelengths, we confirm a blue spectral feature similar to the result of the Monitor field. We find that the result of this study is consistent with Spitzer Space Telescope observations at 3.6 μm. The origin of the excess fluctuation in the near-infrared background remains to be determined, but we could exclude zodiacal light, diffuse Galactic light, and unresolved faint galaxies at low redshift based on the comparison with mid- and far-infrared brightness, ground-based near-infrared images.

Key words: galaxies: clusters: intracluster medium – galaxies: high-redshift – infrared: diffuse background – methods: data analysis – stars: Population III – zodiacal dust

1. INTRODUCTION

It has been known that there exists excess extragalactic background light (EBL) in the near-infrared from the data of DIRBE on board Cosmic Background Explorer (Dwek & Arendt 1998; Hauser et al. 1998; Wright & Reese 2000; Cambresy et al. 2001; Arendt & Dwek 2003; Levenson et al. 2007) and the Near-infrared Spectrometer (NIRS) on board Infrared Telescope in Space (IRTS; Matsumoto et al. 2005). Recent analysis of data obtained by AKARI (Tsumura et al. 2013) shows a consistent result with them. The excess EBL is several times brighter than the integrated light of galaxies and shows a blue stellar-like spectrum. Since the near-infrared sky brightness is dominated by the zodiacal light, which is sunlight scattered by interplanetary dust (IPD), the absolute level of the excess EBL has an uncertainty due to inaccuracies in the model of zodiacal light. On the other hand, the fluctuation of near-infrared sky brightness could provide complementary information on the origin of excess emission since the zodiacal light is fairly smooth (Pyo et al. 2012). Recent studies of Kashlinsky et al. (2005, 2007) and Matsumoto et al. (2011, hereafter Paper 1) using the data taken by space telescopes found excess fluctuations of the sky brightness at angular scales of a few hundred arcseconds that cannot be explained with known emission components. More recently, Cooray et al. (2012b) and Kashlinsky et al. (2012) found that an almost flat angular spectrum of the fluctuation extends up to angular scales of a degree by using data sets from Spitzer at 3.6 and 4.5 μm. Characteristic features of the observed fluctuation are a blue stellar-like spectrum and a good spatial correlation between different wavelength bands. Zemcov et al. (2014) measured significant excess fluctuations at 1.1 and 1.6 μm using the data from Cosmic Infrared Background Experiment (CIBER).

One of the intriguing interpretations regarding the origin of the near-infrared excess EBL is the Population III stars (Kashlinsky et al. 2005; Paper 1) that cannot be identified individually because of their faintness. However, there are some questions and debates about such an interpretation. According to Madau & Silk (2005), a large excess of the EBL at near-infrared wavelength bands requires a large number of Population III stars in the early universe and produces an excess of heavy elements at high redshifts. Also TeV γ-ray observations prefer a lower near-infrared EBL than the observed one to explain absorption features in γ-ray spectra of blazars (Aharonian et al. 2006; Gilmore et al. 2012; Meyer et al. 2012; H.E.S.S. Collaboration 2013). In addition, recent simulations predicted smaller fluctuations than observational measurements by an order of magnitude (Cooray et al. 2012a; Fernandez et al. 2012; Yue et al. 2013a). Cooray et al. (2012b) have argued that the intrahalo light (IHL) due to the stars that escaped from galaxies can explain the observed excess fluctuation at large angular scales.

Clearly, more observational studies are necessary to understand the nature of the infrared background radiation. In this study, we extend the scope of our previous analysis of the AKARI Monitor field data (Paper 1) for fluctuation of the sky brightness to a larger angular scale by using the north ecliptic pole (NEP) deep survey data taken by AKARI (Matsumura et al. 2006). Compared to the previous study with the Monitor field, the NEP deep field has shorter exposure time but larger areal coverage, enabling us to investigate fluctuations of the sky brightness at larger angular scales up to ~1000′. This work is complementary to recent observational studies (Cooray...
et al. 2012b; Kashlinsky et al. 2012; Zemcov et al. 2014) in the sense that we also try to find the existence of spatial fluctuations at a larger angular scale, but at different wavelengths and in different regions of the sky. The fluctuation spectra over a wide range of angular scale as well as the spectral shape would be important for the interpretation of the nature of the near-infrared background radiation.

This paper is organized as follows. In Section 2, we present observational data of the NEP deep field, pre-processing of the raw image, and other procedures for data reduction. In Section 3, we describe power spectrum analysis to measure fluctuations of the sky brightness, and we discuss the possibility of fluctuations caused by instrumental effects in Section 4. Correction of the fluctuation spectrum and error estimation are treated in Section 5. The contribution of foreground components is described in Section 6. In Section 7, the result of this study is discussed. We summarize our results in the final section.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

AKARI is an infrared space telescope developed and launched by Japan Aerospace Exploration Agency (JAXA). Details of the mission and its focal plane instruments are described in Murakami et al. (2007) and Onaka et al. (2007). AKARI carried out a number of wide-area surveys in the near-, mid-, and far-infrared wavelength bands. AKARI made wide and deep surveys in the NEP region (Matsuhara et al. 2006; Wada et al. 2008; Kim et al. 2012). The survey of the NEP deep field started in 2006 May with all nine wavelength bands of the Infra-Red Camera (IRC) that is one of the focal plane instruments (see Onaka et al. 2007 for a detailed description of this instrument) ranging from 2.4 to 24 μm, and performed about 270 pointed observations over a period of one year, covering nearly a circular area of 0.4 square degrees (Figure 1).

Among three near-infrared wavelength bands, we used N2 (2.4 μm) and N3 (3.2 μm) for this study, as N4 (4.1 μm) had a shorter exposure time than the others. The Astronomical Observation Template (AOT) of the NEP deep field is IRC05, which performed five sets of exposures (five images) without dithering for one near-infrared wavelength band during one pointed observation. The exposure time for an image is 65.4 s. The field of view (FOV) of an image is about $10^\prime$ × $10^\prime$, and the pixel scale is 1.7′.6. Further information on observations is available in the IRC data user manual (Lorente et al. 2008).

2.2. Pre-processing

We used the AKARI IRC imaging pipeline (version: 070908) for most of the pre-processing of each image (Lorente et al. 2008). However, a few procedures, such as dark subtraction, flat field correction, and aspect ratio resampling, were treated separately to improve the quality of the image. In the ordinary pipeline, a superdark frame that was made by combining about a hundred dark frames taken during LMC observations is used as a default to subtract dark current. However, the ordinary pipeline with superdark frame could not be used to estimate different enhancement of dark current at each pixel in the array when the telescope was exposed to a large number of cosmic rays. For this reason, Tsumura & Wada (2011) studied a new dark subtraction method that is capable of estimating the different response of dark current at each pixel even when images were exposed to many cosmic rays.

For the correction of flat field, we made self flat templates using all the NEP deep field images taken during the period when stray light was negligible. About 210 images in the NEP deep field were used to make a self flat template for each band. To make a self flat template, bright pixels in the image were masked by a clipping procedure to remove real objects, cosmic rays, and some prominent artifacts such as multiplexer bleed (MUXbleed hereafter) trails near very bright objects (Kim et al. 2012). On the other hand, faint pixels that were affected by various kinds of artifacts were treated manually. We examined every image and manually masked faint artifacts such as bad pixels, column pulldown, and center of saturated objects. Eventually, we obtained self flat templates that show an improved feature of flat field and describe systematically faint regions in all images. Some stripes, which can induce artificial fluctuations toward the horizontal direction of each image, are seen after applying the correction for the aspect ratio. To prevent such stripe-like artifacts, we adopted the “nearest” option instead of “linear” option for resampling of pixel values.

2.3. Correction of Instrumental and Time-varying Components

After pre-processing, additional correction procedures to remove instrumental effects and the zodiacal light contribution are needed. The first additional procedure is related to MUXbleed. Observed images of the NEP deep field contain many bright objects, and some of them induced MUXbleed. MUXbleed manifests as bright stripes along the horizontal...
direction of each image caused by bright objects or strong cosmic rays. MUXbleed stripes do not give any significant problem in this study because they can be easily removed by the clipping procedure. However, we found that the pixels in the upper region of a MUXbleed trail become fainter than those in the lower region. In Figure 2, one example of an image (pointing ID: 2110163) and the average pixel value of background for each row is presented to illustrate the MUXbleed problem. As shown, there is a large jump in pixel values across the MUXbleed trail. Unfortunately, MUXbleed occurs rather frequently in the NEP deep imaging data. Among the selected images for this study, about 76% and 78% for 2.4 and 3.2 μm, respectively, suffer from the MUXbleed effect. It would be best to exclude all pixels whose values are affected by MUXbleed, but we need to use such pixels in order not to reject too many. For this reason, we tried to correct for MUXbleed rather than abandoning all affected pixels. In Figure 2, the left image and graph show a state before correcting for the MUXbleed effect, whereas the right parts show a state after the correction. Open circles represent the average background value of each row, and the dotted line in the graph shows the position of MUXbleed. We assumed that the effect of the MUXbleed reaches the dotted-dashed line. The solid line in the left graph is the linear fit of data points that are regarded as not having been affected by MUXbleed. In other words, the dashed line is treated as a value of the background of the image when the MUXbleed problem does not exist. Correction for the MUXbleed problem was done by using the difference between the solid line and dashed line in the left graph. In Section 4, we try to confirm the validity of the result of MUXbleed correction by using the area where the effect of MUXbleed is small in the mosaic image.

The second additional procedure is related to the zodiacal light. In order to make an accurate mosaic image, we have to correct for the seasonal variation of the zodiacal light. Because the axis of Earth’s orbit is slightly inclined from that of the IPD cloud, the zodiacal light toward the NEP shows variation over the observational period. To correct for such an effect, we tried to fit the sky brightness by using a sinusoidal function with the assumption that the spatial distribution of the zodiacal light is smooth at high ecliptic latitude (Kelsall et al. 1998; Pyo et al. 2012). The explicit form for the intensity of the zodiacal light as a function of the Earth’s heliocentric ecliptic longitude, \( l \), can be written as

\[ I(l) = a \sin(l - b) + c, \]

where parameters \( a, b, \) and \( c \) represent amplitude, phase angle, and mean sky brightness, respectively, which can be determined by fitting the observed sky brightness. We used MPFIT\(^6\) package (Markwardt 2009) for sinusoidal fitting, and the results are presented in Table 1. In Figure 3, we show the fitting result together with the sky brightness data in two near-infrared bands. We subtracted the fitted function from each image to correct for the time variation of zodiacal light.

The MUXbleed and time variation of zodiacal light may induce artificial spatial fluctuation of the sky brightness. Moreover, when we make a mosaic image, the sky level of each image is adjusted by using overlapped regions between neighboring images. Therefore, the two additional correction procedures stated above should be applied before making a mosaic image.

2.4. Source Subtraction

According to Takagi et al. (2012) and Kato et al. (2012), the point-spread function (PSF) of AKARI IRC images is not circular but elongated along a certain direction due to jitters in the satellite pointing, and the direction of elongation varied depending on the position in the mosaic image because of variation of the position angle of each image. Therefore, source subtraction should be done before making a mosaic image. The procedure for removing resolved objects in the image consists

\(^6\) http://purl.com/net/mpfit
of two parts: clipping and PSF subtraction. Specific procedures for source removal are almost the same as those of the previous study for the Monitor field (Paper 1), but we applied additional procedures for saturated bright objects and extended objects to minimize the possible contamination of the relatively faint wing parts of such objects. For saturated objects, the sky level of an individual object was estimated using a mean of pixel values within an annulus whose inner and outer radii are proportional to the brightness of the object, and then we additionally applied a circular mask whose radius was extended until the residual of the object becomes the sky level. For extended objects that were identified by stellarity index in the catalog of optical images (Hwang et al. 2007), we also applied additional circular masks with the same way as for saturated objects.

2.5. Mosaic Images

AKARI NEP deep survey observations started in 2006 May, but data taken in the northern sky during 2006 May, June, and July were affected by scattered Earthshine (Wada et al. 2007). For this reason, we excluded the data taken between April and August to avoid the Earthshine problem. We selected 86 pointed observations for two bands taken from 2006 September to 2007 March. We further rejected additional images for any bright object. We use this small area to confirm the validity of the correction for the MUXbleed problem. We can measure fluctuations of the sky brightness by using mosaic images. Basic parameters of the mosaic image of the NEP deep field after the correction procedures are listed in Table 2. In the bottom panel of Figure 4, smoothed mosaic images made by averaging of neighboring pixels within a circular shape filter with a diameter of 100″ are presented to show spatial structure more clearly. Although spatial structure is seen in the smoothed mosaic images, its pattern appears to be somewhat different for each band. This could imply the possible existence of artificial structure. More careful assessment of such a phenomenon is discussed later in Section 4.

3. POWER SPECTRUM ANALYSIS

We used power spectrum analysis to measure spatial fluctuations of the NEP deep field following the previous works (refer to Paper 1 for a more detailed description of power spectrum analysis). The top panel of Figure 5 represents the fluctuation spectra, \( \left[ q^2 P(q)/2\pi \right]^{1/2} \), for the mosaic images between inner and outer annuli is too small for that. Third, bad images that show poor stability during observation or various artifacts including cosmic rays were also rejected. Eventually we used 75 and 68 images for 2.4 and 3.2 μm, respectively, out of 34 pointed observations. These images after source subtraction with pre-processing and two additional corrections were combined to make mosaic images for two bands by using the software Montage.7 Montage adjusts the sky level of each image by using overlapping regions among adjacent images during mosaicking. Because the sky level of an image is usually not exactly consistent with that of the neighboring image in the overlapping region, a sky adjustment procedure while making mosaic images further reduces artificial fluctuations.

In order to guarantee a stable mosaicking procedure, sufficient overlapping regions among adjacent images are necessary. For this reason, although the source subtraction procedure was performed before mosaicking, further masking for saturated bright objects and extended objects was conducted in the mosaic image to leave sufficient overlapping regions for mosaicking. Moreover, instrumental and observational artificial components, such as bad pixels, column pulldown, center of the saturated objects, and MUXbleed, were removed in advance before mosaicking because they hinder the sky matching process because of their different pixel values and shapes in the adjacent images. After mosaicking, pixels that remain at least in two pointed observations are selected for the study (the top panel of Figure 4). Because pixels that survive in only a single pointed observation do not have a chance to suppress the contributions of artificial components, they are more likely to be affected by artifacts such as leakage of stray light (see Section 4 for details). In addition, it is hard to recognize whether the boundary region of an image is affected by objects just outside the image. In order to avoid such contamination, we selected pixels that also survive in at least one additional adjacent pointed observation.

The small area denoted by a dashed line box in Figure 4 represents the region where the effect of MUXbleed is small compared to the other regions because this area does not have any bright object. We use this small area to confirm the validity of the correction for the MUXbleed problem. We can measure fluctuations of the sky brightness by using mosaic images. Basic parameters of the mosaic image of the NEP deep field after the correction procedures are listed in Table 2. In the bottom panel of Figure 4, smoothed mosaic images made by averaging of neighboring pixels within a circular shape filter with a diameter of 100″ are presented to show spatial structure more clearly. Although spatial structure is seen in the smoothed mosaic images, its pattern appears to be somewhat different for each band. This could imply the possible existence of artificial structure. More careful assessment of such a phenomenon is discussed later in Section 4.

### Table 1

| Band | \( a \) (nW m\(^{-2}\) sr\(^{-1}\)) | \( b \) (deg) | \( c \) (nW m\(^{-2}\) sr\(^{-1}\)) |
|------|---------------------------------|---------------|---------------------------------|
| N2   | 11.70 ± 0.010                   | 66.20 ± 0.089 | 113.92 ± 0.016 |
| N3   | 6.70 ± 0.004                    | 61.62 ± 0.055 | 71.26 ± 0.005 |

Figure 3. Sky brightness of each image for two bands. Open squares and open circles correspond to 2.4 and 3.2 μm, respectively. Solid lines are sinusoidal fitting of the sky brightness as a function of heliocentric ecliptic longitude of Earth. The error bar represents 1σ error, which is too small to be apparent.

Figure 4. Smoothed mosaic images made by averaging of neighboring pixels within a circular shape filter with a diameter of 100″.
and subset analysis. Filled circles contain contributions of instrumental noise and unresolved faint objects as well as the background component. We estimated the contribution of each component separately to extract the background component. Subset analysis is intended to estimate the fluctuation spectrum of instrumental noise in the mosaic image and to confirm whether structure observed in the mosaic image is of celestial or cosmic origin. To perform subset analysis, all the images were divided into two subsets composed of alternating pointed observations in sequence from the left side of the mosaic image, and the difference of the two subsets was taken. This difference will erase persistent features in the sky, and leave instrumental noise that consists of random noise and artificial features in the mosaic image. As shown in the top panel of Figure 5, the subset analysis reveals a significantly smaller fluctuation than that of the mosaic image. However, the result of subset analysis shows larger fluctuation than that of random noise at large angular scale. As discussed later in Section 4, this implies that artificial structure could remain in the mosaic image. A difference of fluctuation spectra between the subset analysis and random noise represents the amount of contamination by the possible artificial structure. At angular scales larger than 100″, a mean power spectrum, $P_2(q)$, due to artificial structure reaches up to about 10% and 12% of that of the mosaic image for 2.4 and 3.2 $\mu$m, respectively. Fluctuation spectra of the mosaic images after quadratically subtracting the results of the subset analysis are presented in the bottom panel of Figure 5.

### Table 2

| Item                             | 2.4 $\mu$m | 3.2 $\mu$m |
|----------------------------------|------------|------------|
| R.A.(J2000), Decl.(J2000)        | $17^h55^m24^s$ | $66^\circ37^\prime32^\prime$ |
| Number of pointed observations   | 17         | 17         |
| Number of images                 | 75         | 68         |
| Mean observation time (minutes)  | 12.0       | 10.9       |
| Mean number of stacked images    | 11         | 10         |
| Limiting magnitude (AB mag)      | 21.4       | 21.8       |
| Percentage of remaining pixels (%) | 39.6     | 39.5       |
| Average sky brightness (nW m$^{-2}$ sr$^{-1}$) | $113.92 \pm 0.016$ | $71.26 \pm 0.005$ |

Figure 4. Mosaic images of the NEP deep field for two bands in equatorial coordinates. Top: final states of the mosaic images. White color represents masked regions. The small area denoted by the dashed line box is the region where the effect of MUXbleed is small compared to other regions in the mosaic image regardless of the correction for the MUXbleed problem. Bottom: smoothed mosaic images whose pixel values are replaced by unweighted averaging of neighboring pixels within a circular shape filter with a diameter of 100″ to show large-scale structures. The size of the mosaic image (solid line box) is 36′ × 25′ for 2.4 $\mu$m and 35′ × 23′ for 3.2 $\mu$m. Note that structures in the mosaic images include artificial as well as real ones in the sky. The mean pixel value of each mosaic image is adjusted to zero.

### 4. CONTRIBUTION OF INSTRUMENTAL EFFECTS

One of the possible origins of the spatial fluctuations of the infrared background is the instrumental effect. The MUXbleed effect could induce artificial fluctuation. In order to check for any possible artificial fluctuations due to insufficient correction for MUXbleed, we used the small area (denoted by a dashed line box in Figure 4) in the mosaic image as a representative region where the effect of the MUXbleed problem is negligible even before MUXbleed correction. In Figure 6, two new fluctuation spectra (solid lines and asterisks) are shown along with the spectra derived in the previous section (open circles). Solid lines represent fluctuation spectra of the small areas
where the effect of MUXbleed is negligible compared to other regions in the mosaic image. In addition, we made another kind of mosaic image for each band composed of images before the correction of MUXbleed. Their fluctuation spectra are presented as asterisks. Because the effect of MUXbleed is not confined to a single image but propagates to all regions during the mosaicking procedure, asterisks show larger fluctuations than open circles at angular scales larger than \(100''\). Moreover, open circles have similar fluctuation power to that of solid lines at angular scales up to a few hundred arcseconds, implying that a significant amount of the MUXbleed problem has been removed by the correction procedure shown in Figure 2. We can see that the whole mosaic image after MUXbleed correction shows similar fluctuation power to the small area where the effect of MUXbleed is negligible. We conclude that the correction for the MUXbleed problem was effective.

Meanwhile, as shown in the top panel of Figure 5, the result of subset analysis gives larger fluctuation than that of random noise at large angular scales. This means that subsequent pointed observations toward the same field show different structures from each other, which may be caused by temporary instrumental effects. Although contributions of artificial components are estimated and subtracted from the final result by subset analysis, we attempted to identify the cause of large fluctuations in subset analysis to ensure the result of this study. We made two subsets that contain alternating images (i.e., alternating exposures in a pointed observation), rather than alternating pointed observations, in sequence from the left side of the mosaic image. As presented with asterisks in Figure 7, the result of this new subset analysis shows a smaller fluctuation than the previous one and becomes closer to the fluctuation of random noise shown as a dotted line at large angles. This implies that there exist artificial structures in each pointed observation, which persist at least during a period of one pointed observation. In the new subset analysis, an image in one subset shares the same FOV with its counterpart in the other subset due to there being no dithering between them. Therefore, although there are artificial structures in each image, they are canceled out by taking a difference of two subsets if artificial structures are unchanged during a period of one pointed observation. As a result, the new subset analysis shows a nearly random-noise-like fluctuation spectrum.

There are several candidates that can induce artificial structures in each pointed observation. First, errors occurring during pre-processing of raw imaging data can be a source of the artificial structure. However, because we used the same pre-processing method as that of the previous study (Paper 1) and the result of subset analysis in the previous study shows random-noise-like behavior, problems in pre-processing are not likely to be the main reason for the large fluctuation at large angular scales. Another possible origin is the error that arises during source subtraction procedures by using the PSF. Because the PSF of the AKARI IRC image is not symmetric but elongated and the direction of PSF elongation in the mosaic image varies depending on the position angle of the pointed observation, there is a possibility of distinct residuals in each pointed observation after PSF subtraction. If so, the effect of PSF subtraction may produce an artificial fluctuation in subset analysis at small angular scales of a few tens of arcseconds as well as at large angular scales. As shown in Figure 7, the large fluctuation in subset analysis mainly appears at angular scales larger than \(100''\), whereas the result of subset analysis follows the behavior of random noise at small angular scales. Therefore, the error related to the PSF subtraction procedure is not likely to be the main reason for the large fluctuation at large angular scales in the subset analysis.

**Figure 5.** Top: fluctuation spectra, \(\left[ q^2 P_2(q) / 2\pi \right]^{1/2} \), of the mosaic image (filled circles) and subset analysis (open circles). The dotted line represents the expected slope from random noise. Bottom: fluctuation spectra of the mosaic images after quadratically subtracting those of subset analysis. \(P_2(q)\) and \(q\) represent power spectrum and angular wavenumber, respectively. Error bars show 1σ error.
The remaining probable cause is temporary instrumental effects such as stray light that remain as distinct structures in each pointed observation. We paid particular attention to the fact that stray light can change during a period of subsequent pointed observations. To test the stray light as a possible origin of the artificial fluctuation, we made more detailed analysis of the imaging data of the Monitor field. We found 13 pointed observations of the Monitor field that were carried out during the same period, and 13 images were made by stacking three images of the N2 band in each pointed observation separately. After that, 13 images were subtracted from the entire stacked image of the N2 band in the Monitor field separately. We present the result in Figure 8, which shows distinct structure in each pointed observation. They are artificial structures because real structure is removed by subtraction of the entire stacked image of the Monitor field. The last image in Figure 8 was made by stacking 13 images; it shows negligible structure and indicates that artificial structures in each pointed observation have a more random nature than those in other pointed observations. The test with the Monitor field data has some advantages in identifying possible candidates that could lead to the large fluctuation in subset analysis. For example, because they do not contain the MUXbleed problem and subset analysis of the Monitor field shows similar behavior to random noise (Paper 1), we can exclude the MUXbleed problem and errors that occurred during pre-processing from the possible candidates. In addition, because only a clipping procedure was used to remove objects in this test, we can also exclude errors that occurred during the PSF subtraction procedure as a possible candidate.

We made the same test for the N3 band to examine the behavior of artificial structures in the Monitor field. Note that the AOT of the Monitor field is IRC03, which is different to that of the NEP deep field. IRC03 performed three sets of images for three near-infrared wavelength bands of the IRC alternately during one pointed observation, and filter wheel change or dithering was applied between exposures. We also found artificial structures in the N3 band and obtained linear Pearson correlation coefficients of 0.112 (mean) ± 0.158 (standard deviation) with those of the N2 band in each pointed observation. Evidently there is no statistically significant correlation between them even in each pointed observation. That is to say, unlike artificial structures in the NEP deep field, those in the Monitor field vary frequently even during a period of one pointed observation. A probable candidate that can explain both the existence of artificial structures in the two fields and the difference of their behaviors is a contribution of stray light that depends on the position of the filter wheel. Although we used imaging data that were observed during a period of little stray light, we could not exclude some leakage of stray light that has contaminated the images. In the case of the NEP deep field, because there is no operation of a filter wheel during a pointed observation, the pattern of the stray light remained nearly the same for different images taken during one pointed observation. On the other hand, in the case of the Monitor field, because stray light could have been scattered differently due to operation of the filter wheel during a pointed observation, we can expect a different shape of artificial structure in each image. Therefore, a distinct artificial pattern may remain in each pointed observation of the NEP deep field more clearly than that of the Monitor field. Moreover, such artifacts are rarely suppressed during mosaicking due to the small number of stacked images per field. To evaluate the contribution of artificial structures quantitatively, we estimated fluctuation spectra of the images in Figure 8. The results for 13 pointed observations are presented as solid lines in Figure 9, their mean is presented as filled circles, which show a larger fluctuation than the dotted line at large angular scales. The fluctuation spectrum of the last image denoted by open circles shows a small deviation from random noise and smaller overall fluctuation power than those of other images.

The contribution from artificial structure in the mosaic image of the NEP deep field can be estimated by quadratically subtracting the fluctuation spectrum of random noise from that of subset analysis in the top panel of Figure 5, which becomes 0.098 and 0.053 nW m\(^{-2}\) sr\(^{-1}\) for 2.4 and 3.2 \(\mu\)m, respectively, as a mean at angles between 100° and 350°. We can expect such a quantitative contribution of artificial structure of the NEP deep field by converting that of the Monitor field presented in Figure 9. The difference between filled circles and
the dotted line represents fluctuation due to artificial structure in each pointed observation of the Monitor field. For the case of the N2 band, the mean difference at angular scales larger than 100" is about 0.092 nW m\(^{-2}\) sr\(^{-1}\). In a pointed observation of the Monitor field, the amplitude of artificial structure becomes \(\sqrt{3}\) times weaker as three images with different shapes of artificial structure are stacked with dithering. However, such a reduction would not occur for the NEP deep field because images with similar shape of artificial structure are stacked without dithering. As a result, in the NEP deep field, we can expect that the contribution of artificial structure in each pointed observation is \(\sqrt{3}\) times larger than that of the Monitor field. Finally, because the mosaic image for the N2 band in the NEP deep field is covered by 3.4 pointed observations per field on average, the contribution of artificial structure becomes \(\sqrt{3.4}\) times weaker in the mosaic image, resulting in 0.086 nW m\(^{-2}\) sr\(^{-1}\). Similarly we estimated the fluctuation due to artificial structure to be 0.049 nW m\(^{-2}\) sr\(^{-1}\) for the N3 band in the NEP deep field. Such a result corresponds to about 90% of the residual fluctuation of subset analysis over random noise shown in the upper panel of Figure 5. Therefore we conclude that the contribution of temporary instrumental effects, most likely stray light, may be the most prominent cause of the large fluctuation in subset analysis. Although this test is valid only within angular scales of a few hundred arcseconds, it can give a hint of the large fluctuation of subset analysis at angular scales larger than a few hundred arcseconds.

Although we examined artificial components in the mosaic image and their possible origin, it is difficult to correct them more accurately due to their random nature in each pointed observation. To reduce further the contribution of artifacts with random nature, we need a larger number of stacked images per field.

5. CORRECTION AND ERROR ESTIMATION

5.1. Corrections of the Fluctuation Spectrum

Fluctuation spectra in the bottom panel of Figure 5 were further corrected to remove instrumental and systematic effects. Corrections of the fluctuation spectra were conducted as follows. The power spectrum after the corrections can be expressed as

\[
P_2(q) = \frac{M^{-1}(q) \tilde{B}(q)}{T^2(q) B(q)},
\]

where \(M(q)\) is a mode coupling matrix, \(T(q)\) is a map-making transfer function, \(B(q)\) is a beam transfer function, and \(\tilde{B}(q)\) represents the power spectrum before the corrections.

Observed fluctuation is affected by the presence of a mask in the mosaic image. In order to correct the observed fluctuation, we examined the effect of the mask on each data point separately by simulation (Cooray et al. 2012b; Zemcov et al. 2014). We made a simulated image that has a unit value of fluctuation power at a certain angular scale but no fluctuations at other angular scales. By adopting the mask of the mosaic image on the simulated image, we can estimate how the mask converts the unit fluctuation power at a certain angular scale into those of other angular scales. Simulations were iterated 100 times for each data point by adjusting the phase of a complex number in Fourier space, and the result was expressed as a matrix, \(M(q)\), each row of which corresponds to the result of simulation for each data point. The mode coupling matrix can be used to estimate the effect of the mask on the fluctuation, whereas its inverse, \(M^{-1}(q)\), can be used to recover the intrinsic fluctuation. To check the usefulness of the mode coupling matrix, we introduced a seed fluctuation that has similar fluctuation power to the observation and produced 500 simulated images with identical fluctuation spectrum to the seed fluctuation. Each simulated image corresponds to a random realization of the seed fluctuation by adjusting phase in Fourier space. Fluctuation spectra of the simulated images with the mask of the mosaic image were recovered by the inverse of the mode coupling matrix. As shown in Figure 10, the mean of recovered fluctuations (solid line) is well matched with the seed fluctuation (open squares). By using the simulated mask pattern, we confirmed that an error of the recovered fluctuation is related to the portion of the mask. Because the FOV of the NEP deep field is not rectangular, outside the FOV is also treated as a mask in the simulation. Therefore such a large portion of the mask induces a large error in the recovered fluctuation. Figure 10 shows that the mode coupling matrix is efficient in estimating the mean effect of the
Figure 8. Here we show 13 images (N2 band) with pointing IDs (numbers above images) that are produced by subtracting the stacked image of each pointed observation of the Monitor field separately from the entire stacked image of the Monitor field. The last image is the stacked image of 13 images with pointing IDs. Images are smoothed by unweighted averaging of neighboring pixels within a circular shape filter with a diameter of 50″ to emphasize structures. Black color represents masked regions. The diameter of each image is about 550″. Images are aligned with the equatorial coordinates. The mean pixel value of each image is adjusted to zero. The scale range corresponds to ±5σ of 13 images with pointing IDs.
mask for multiple realizations. Because there is no information about the intrinsic fluctuation spectrum of the NEP deep field, we do not know how it is to be converted by the mask of the mosaic image. Therefore, we adopted the mean effect of the mask for the correction. Two components are considered for the error of the mode coupling matrix. One is the systematic error that can be measured by the difference between seed fluctuation and recovered fluctuation in Figure 10. The other is the statistical error as measured by the standard deviation of the recovered fluctuations for many different realizations. Two components are added quadratically, and it becomes the most dominant component of the error budget at angular scales larger than 300″. However, at that angular scale, mean errors of the mode coupling matrix for 2.4 and 3.2 μm, 0.086 and 0.054 nW m⁻²sr⁻¹, are smaller than observed fluctuations for 2.4 and 3.2 μm, 0.177 and 0.129 nW m⁻²sr⁻¹. Fluxuation power at a small angular scale can be reduced due to the effect of PSF. Although we used an analytic form for the PSF to subtract wing parts of detected objects, it is difficult to define asymmetric central parts of objects by using the analytic function. Therefore, to correct for the effect of PSF on the fluctuation, we derived the PSF of the NEP deep field by stacking point objects. We stacked 127 and 85 point objects for 2.4 and 3.2 μm, respectively, to obtain PSFs and their power spectra of these bands. The beam transfer function in Figure 11 represents the power spectrum of PSF that is normalized to be 1 for 2.4 and 3.2 μm, respectively. The PSF transfer function for 3.2 μm is reduced to about 2% of the original fluctuation power similar to the observed one in order to mimic the real sky. Individual frames identical to the size of an AKARI IRC frame have been extracted from the simulated image. We then assigned the same noise and sky levels, and applied the same masking patterns with observed frames to all extracted frames. The intensity of the random noise in the simulated image was determined by the result of subset analysis at small angular scale, and the sky level of each simulated image was determined using the value in Figure 3. Finally, they were combined through the same mosaicking procedure using Montage as we did for the observed images. Simulations were repeated 1000 times, and original fluctuation spectra were compared with those of remade mosaic images. The map-making transfer function in Figure 12 represents the mean of the ratio of remade fluctuation spectra to original ones, and the error bar represents a standard deviation of 1000 simulations. First of all, at large angular scale, we were able to reproduce the original fluctuation for 2.4 μm, while we found fluctuations larger by about 10% at the largest angular scale for 3.2 μm. One possible cause of such a difference is a difference in overlapping regions between 2.4 and 3.2 μm: there are more overlapping region in 2.4 μm than in 3.2 μm. However, this is mainly due to the order of data reduction procedures in this study. Because we masked some pixels before making the mosaic image to remove objects, the overlapping region between adjacent images becomes small. This may be the main reason for additional artificial fluctuations at large angular scale for 3.2 μm. To confirm this, we obtained the map-making transfer function for 3.2 μm without masking before making the mosaic image. At large angular scale, we found that the additional fluctuation is reduced to about 2% of the original fluctuation for 3.2 μm. Also the standard deviation of 1000 simulations decreased by about one third compared to the result.
On the other hand, significant suppression in the fluctuation spectrum is apparent at small angular scale due to smoothing effect by resampling of pixel values during the mosaicking procedure. We found that such suppression is mainly induced by instrumental random noise rather than celestial objects at angular scales smaller than 10″. Therefore, we did not use the fluctuation spectrum at angular scales smaller than 10″ for further analysis since the measured fluctuations at such small scales are dominated by shot noise and lie beyond our interests. To correct for the effect of the map-making transfer function, the observed fluctuation spectrum at angular scales smaller than 10″ was divided by the map-making transfer function. The error was included in the final error budget after applying the error propagation formula. At angular scales larger than 100″, the mean of the error related to the map-making transfer function is 0.009 and 0.006 nW m⁻² sr⁻¹ for 2.4 and 3.2 μm, respectively, which are smaller than observed fluctuations by an order of magnitude.

In Figure 12. On the other hand, significant suppression in the fluctuation spectrum is apparent at small angular scale due to smoothing effect by resampling of pixel values during the mosaicking procedure. We found that such suppression is mainly induced by instrumental random noise rather than celestial objects at angular scales smaller than 10″. Therefore, we did not use the fluctuation spectrum at angular scales smaller than 10″ for further analysis since the measured fluctuations at such small scales are dominated by shot noise and lie beyond our interests. To correct for the effect of the map-making transfer function, the observed fluctuation spectrum at angular scales smaller than 10″ was divided by the map-making transfer function. The error was included in the final error budget after applying the error propagation formula. At angular scales larger than 100″, the mean of the error related to the map-making transfer function is 0.009 and 0.006 nW m⁻² sr⁻¹ for 2.4 and 3.2 μm, respectively, which are smaller than observed fluctuations by an order of magnitude.

5.2. Systematic Errors

In the previous section, errors related to the mode coupling matrix, the beam transfer function, and the map-making transfer function were described. In addition, flat field error and an error due to residuals of detected objects were investigated as possible systematic errors because their contributions to the observed fluctuation spectrum may be significant. Even a small amount of flat field error in an image can be accumulated in the mosaic image during the mosaicking procedure. Therefore, artificial fluctuation due to flat field error can affect the final fluctuation spectrum. In order to obtain the flat field error, we stacked 190 and 220 images for 2.4 and 3.2 μm, respectively, with (x, y) coordinates after masking detected objects. After that, the obtained flat pattern is assigned to individual frames for each band and the mask pattern and sky level were also assigned to them. Finally, they were...
combined through the same mosaicking procedure using Montage as we did for the observed images, and fluctuation spectra were estimated. The result of this simulation can be treated as an upper limit due to flat field error because the simulated image also contains celestial fluctuation and fluctuations due to other artifacts. As shown in Figure 13, fluctuation spectra of the simulated images are smaller than observed fluctuations at all angular scales, indicating that flat field error is not significant and not severely accumulated in the mosaic image during the mosaicking procedure.

Residuals after masking and subtraction of detected objects can also make some contributions to the final result. If there remain residuals of detected objects, their contributions are most significant just outside of the masked region of the objects. For this reason, we examined residual within five pixel layers from the masked region by comparing the sky level of each detected object. After that, to make a simulated image with the size of the mosaic image, the mean of the residual of each detected object is assigned to that region, while zero value is assigned to other regions. Instead of the real residual, the mean of the residual is assigned to suppress the contribution of noise and undetected faint objects in that region. As shown in Figure 13, the contribution from the residual of detected objects is also smaller than observations, especially at large angular scale, implying that the observed excess fluctuation at large angular scale is not affected by the residual of the detected objects.

5.3. Corrected Fluctuation Spectrum

Fluctuation spectra after corrections by the mode coupling matrix, the beam transfer function, and the map-making transfer function are presented in Figure 13. As shown, the mosaic images have excess fluctuations, i.e., residual fluctuations over the shot noise, at large angular scales. Errors related to corrections and two systematic errors are also plotted separately along with the 1σ error of Fourier elements of each bin. Error bars of the filled circles are their quadratic sum. The effect of shot noise originating from unresolved faint galaxies was estimated by using simulated images of the same size as the mosaic image containing objects fainter than the limiting magnitude. We used the power-law distribution, $N(m) \propto m^{-0.23}$ (Maihara et al. 2001), of the number of artificial objects of magnitude $m$ in a unit magnitude interval for the generation of simulated images. The normalization was done based on the number of detected objects in the mosaic image. The ARTDATA package of the Image Reduction and Analysis Facility (Tody 1986) was used to generate a list of randomly distributed objects and to assign them on the simulation image. Before the estimation of the fluctuation spectrum, the mask pattern of the mosaic image was applied to the simulated image. We made 100 simulated images for each band and the estimated mean of 100 fluctuation spectra. The overall amplitude of fluctuation is determined by the limiting magnitude. The observed fluctuation spectra at small angular scale well match the shot noise with the limiting magnitude (AB) of 21.4 and 21.8 for 2.4 and 3.2 μm, respectively.

6. CONTRIBUTION OF FOREGROUND SOURCES

6.1. Zodiacal Light

Because zodiacal light is the most significant contributor to brightness of the near-infrared sky, it is a probable candidate to explain the excess fluctuation of the mosaic image. Pyo et al. (2012) investigated the spatial fluctuation of the mid-infrared sky by using the Monitor field data set of AKARI and found
very small residual fluctuation over photon noise. Since we expect that the fluctuation due to zodiacal light does not depend on the wavelength, we adopted their results of $\sim 0.03\%$ of the sky brightness at the 18 $\mu$m band as an upper limit of fluctuations due to zodiacal light in the near-infrared sky at angular scales larger than 100$''$. If we estimate fluctuations by using the results in the mid-infrared sky, the upper limits of fluctuations due to zodiacal light become 0.034 and 0.021 nW m$^{-2}$ sr$^{-1}$ at 2.4 and 3.2 $\mu$m, respectively. Due to the motion of the Earth, the IPD column along the line of sight toward the NEP continuously changes during the observation period. The fluctuation due to zodiacal light could have been additionally reduced during mosaicking because subsequent pointed observations toward the same field might detect a different shape of spatial fluctuations in the zodiacal light. The estimated upper limits due to zodiacal light are clearly smaller than the observed excess fluctuations.

6.2. Galactic and Extragalactic Components

Diffuse Galactic light (DGL), starlight scattered by the interstellar dust, can also be a candidate for the excess fluctuation. Because DGL traces the distribution of the interstellar dust, we examined the far-infrared 90 $\mu$m band that was taken by Far-Infrared Surveyor$^8$ (FIS; Kawada et al. 2007) on board AKARI. Slow scan observations with a scan speed of 15 arcseconds per second and a reset interval of 2 s were carried out to cover the NEP deep region. We processed the raw pointed data with the official FIS slow-scan toolkit (Verdugo et al. 2007). The data reduction tool removed bad data and cosmic rays and corrected for the variation of the detector responsivity. After the dark current subtraction and flat fielding, undetected glitches and other artifacts were removed.

The uncertainties of flux calibration are no more than 20% for the 90 $\mu$m band (Kawada et al. 2007). The processed images were combined to make a mosaic image using the software Montage.

To remove the contribution of discrete objects in the far-infrared mosaic image, we masked pixels whose values exceed three times the standard deviation from mean pixel value, and one layer of pixels around the masked region was additionally masked. About 5% of pixels were masked in this procedure. To estimate the correlation between images with different pixel resolutions, the angular resolution of the far-infrared mosaic image was adjusted to that of the far-infrared mosaic image, and then a mask of the near-infrared mosaic image was applied on the far-infrared image. The left panel of Figure 14 shows that there is no clear correlation between near- and far-infrared images. However, as discussed earlier, because there are some artificial structures in the near-infrared mosaic images, this method has some limited implications. For this reason, we made another examination. The right panel of Figure 14 shows fluctuation spectra of the far-infrared image in both the Monitor field and the NEP deep field. We focused on the fluctuations at angular scales larger than 100$''$ where the shot noise becomes small. The far-infrared images of both fields have similar fluctuation powers at angular scales up to 300$''$, and the NEP deep field does not show any significant increase of fluctuation even at larger angles. Such a result shows that the NEP deep field makes a similar contribution of DGL to the Monitor field. Therefore, we can say that the contribution of DGL is negligible in the NEP deep field by using the result in the right panel of Figure 14.

The clustering of unresolved galaxies fainter than the limiting magnitude of the mosaic image can also be a candidate for the excess fluctuations. Like the previous study with the Monitor field, the feature of observed excess fluctuation with

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$^8$ FIS images are available at http://darts.jaxa.jp/ir/akari.

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Figure 14. Left: correlations between the near-infrared mosaic images and the far-infrared mosaic image at 90 $\mu$m taken by AKARI/FIS. Error bars represent the standard deviations of the noise images. Linear fitted lines are shown as solid lines. The slopes of fitted lines are almost zero (10$^{-3}$ or so), indicating that there are no correlations between near- and far-infrared bands. Right: fluctuation spectra of the far-infrared mosaic image in both the Monitor field (asterisks) and the NEP deep field (open triangles). Because shot noise is a dominant component at small angular scale, we focused on fluctuations at angles larger than $100''$. Error bars show 1$\sigma$ error.
blue spectrum also shows inconsistency with the study by Chary et al. (2008), who proposed that a fraction of fluctuations in the near-infrared background could be induced by red dwarf galaxies. We used the deep imaging observations at the $K_s$ band ($\lambda_c : 2.146 \mu m$) with the Canada–France–Hawaii Telescope (CFHT) Wide-field InfraRed Camera (WIRCam)\(^9\) for the NEP deep field (Oi et al. 2014) for the estimation of the contribution of the clustering of unresolved faint galaxies to the excess fluctuations. To extract sources in the $K_s$ band image, we used SExtractor (Bertin & Arnouts 1996) with the following parameters: DETECT THRESH = 2, DETECT MINAREA = 3, BACKSIZE = 64, BACK FILTERSIZE = 3. The detection limit was estimated by using simulated sources and the same parameter sets of SExtractor to recover them. The 50% detection limit is about 23.5 AB mag, which is deeper than the limiting magnitude of the N2 band and is sufficiently sensitive to detect the main contribution from the clustering of unresolved faint galaxies. The simulation was performed using the detected objects at the $K_s$ band in the area (dotted line box in Figure 1) that covers most regions used in this study. We prepared a simulation image having the same size as the area with the dotted line box and assigned detected objects at the same position on the simulated image. When we make a simulated image with objects fainter than 21.5 AB mag at the $K_s$ band, the fluctuation power of the simulation at small angular scale becomes the same as that of the N2 band mosaic image or shot noise. A result of the simulation is presented as a solid line in Figure 15, which shows larger fluctuation than shot noise at large angular scales. We obtained 0.059 nW m$^{-2}$ sr$^{-1}$ as a mean contribution of the clustering of unresolved faint galaxies at angular scales larger than 300″, which is 2.8 times smaller than the observed excess fluctuation at the same angular scale. Hence we conclude that the contribution of the unresolved faint low-redshift galaxies is not enough to explain the observed excess fluctuations.

\[^9\] http://www.cfht.hawaii.edu/Instruments/Imaging/WIRCam

Sullivan et al. (2007) also investigated angular power spectra of resolved sources at $J$, $K_s$, and $L$ bands. The previous study with the Monitor field (Paper 1) used their model to estimate the contribution of unresolved faint low-redshift galaxies and showed that the estimated contribution is small compared to the observed fluctuation at 2.4 μm. Recently, Helgason et al. (2012) examined fluctuations in the infrared background from known galaxy populations by using large sets of luminosity functions. They applied their model to actual measurements and concluded that the known galaxy population is not likely to be a candidate to explain the observed fluctuations at arcminute scales. Although it is hard to compare their results with ours quantitatively because our simulation only used the detected objects at the $K_s$ band without completeness correction at the faint end of the luminosity function, every study predicts that the contribution of unresolved faint low-redshift galaxies to the fluctuation power is small compared to the observational measurements.

7. DISCUSSION

By using observational data, we found excess fluctuation in the near-infrared background at angular scales up to 1000″. We estimated a mean of the excess fluctuations of 0.26 and 0.11 nW m$^{-2}$ sr$^{-1}$ for 2.4 and 3.2 μm bands, respectively, at angular scales larger than 100″. In Figure 16, we plotted the results (open squares) and those of the Monitor field (open circles). In addition to the similar level of excess fluctuations, the color of fluctuation components of the NEP deep field is found to be similar to that of the Monitor field: both of them show blue spectra, as first observed by the IRTS (Matsumoto et al. 2005) in the excess sky brightness.

By using the result of the NEP deep field, we have extended fluctuation analysis of the Monitor field at angular scales up to 1000″. In Figure 17, the result of the Monitor field (filled circles) is combined with that of the NEP deep field (open squares). The fluctuation spectrum of the NEP deep field connects smoothly with that of the Monitor field and extends without showing any significant variation of fluctuation power at angular scales larger than a few hundred arcseconds. For
comparison with the result of AKARI, that of Spitzer at 3.6 μm (Kashlinsky et al. 2012) is plotted, and is adjusted by the assumption that the spectrum of fluctuating components at the near-infrared wavelength is close to a Rayleigh–Jeans spectrum (∼λ^−3). It is seen that the average excess fluctuation of AKARI is consistent with the result of Spitzer at angular scales between 100′′ and 1000′′.

Although the origin of such excess fluctuation is not yet well understood, we could exclude zodiacal light, DGL, and unresolved faint galaxies at low redshift. One of the remaining possibilities is the contribution from very early objects at z ≳ 10. Theoretical studies have been performed to estimate the fluctuation due to the clustering of high-redshift objects. Their results show that fluctuations of high-redshift objects are different from those of low-redshift objects. Our result can be explained from this point of view. Some theoretical studies with a biased halo model show the fluctuation powers with a turnover feature at around 10′ (Cooray et al. 2004; Kashlinsky et al. 2004), while some other studies predict gradually decreasing fluctuation powers toward large angular scales by considering nonlinear biasing of halos (Fernandez et al. 2010, 2012; Cooray et al. 2012a). The result of this study prefers the latter case, as shown in Figure 17, because our result does not show any significant turnover feature at up to around 10′. However, it should be interpreted carefully because there are only a small number of Fourier elements in the last few data points. Meanwhile, although TeV γ-ray observation prefers a lower level of background brightness than observational measurements in the near-infrared bands to explain the absorption feature in γ-ray spectra of blazars (Aharonian et al. 2006; Gilmore et al. 2012; Meyer et al. 2012; H.E.S.S. Collaboration 2013), it is not a stringent constraint because an alternative explanation of γ-ray spectra of blazars is possible using secondary TeV γ-ray photons produced by interaction between cosmic rays of blazars and EBL (Essey & Kusenko 2010; Essey et al. 2010).

However, theoretical studies predicted smaller fluctuations than observations by about an order of magnitude. Recently, Yue et al. (2013a) investigated the contribution of high-redshift galaxies at z > 5 to the near-infrared background by using simulations with an analytical model. They predicted that the fluctuation amplitude due to z > 5 galaxies would be less than 0.01 nW m^−2 sr^-1 at a few hundred arcseconds in the wavelength range 1.0–4.5 μm, which is ten times smaller than the excess fluctuations in this study and recent observational studies using Spitzer imaging data (Cooray et al. 2012b; Kashlinsky et al. 2012). Therefore, further studies for both theory and observation are required to identify the origin of excess fluctuation in the near-infrared background.

Cooray et al. (2012b) suggested that the extended emission due to IHL can be a candidate to explain the observed fluctuation in the near-infrared background. Although it is an interesting idea, it may be challenging to verify observationally. As discussed in their work, simple masking is not an efficient method to remove diffuse components of faint galaxies. To identify extended components around faint galaxies and to subtract them accurately, we need imaging data with high sensitivity and a sophisticated method for modeling them.

Recently, the rocket-borne instrument CIBER measured the fluctuation of the sky brightness up to 1° angular scale at 1.1 and 1.6 μm bands (Zemcov et al. 2014). Since there exist fluctuations at shorter wavelength than 2 μm, the IHL model is preferred to the contribution from Population III stars in the early universe. They also found that the result of CIBER shows good correlation with the result of Spitzer and the fluctuation at 1.1 μm shows some departure from the Rayleigh–Jeans spectrum.

Yue et al. (2013b) suggested a contribution of direct collapse black holes (DCBHs) at z ≥ 12 as a possible candidate for near-infrared fluctuations. They claimed that the DCBH model can explain observed fluctuations at 3.6 and 4.5 μm and observed cosmic X-ray background/near-infrared background cross-correlation. However, the DCBH model is inconsistent with substantial fluctuations even around 1 μm observed by the CIBER (Zemcov et al. 2014).

To investigate various aspects of the excess fluctuation, more observational studies are needed by using individual imaging data with various FOV, angular scales, and wavelength bands. As one of the scheduled programs for the study of the near-infrared background, the Multipurpose Infrared Imaging System (Han et al. 2010, 2014), launched in 2013 November,

Figure 17. Excess fluctuation of the Monitor field (filled circles) and the NEP deep field (open squares). Their error bars are estimated by the error propagation formula with the error of the shot noise. Solid lines represent the observational result of Spitzer data at 3.6 μm (Kashlinsky et al. 2012), which is adjusted by using a Rayleigh–Jeans spectrum (∼λ^−3) for comparison with the result of AKARI.
is observing a large area of $10^6 \times 10^6$ centered on the NEP for the study of the sky brightness and its fluctuations at 1.1 and 1.6 $\mu$m bands. It will provide new information about the sky brightness in the near-infrared bands at angles up to a few degrees and improve our understanding of the origin of the cosmic infrared background.

8. SUMMARY

We studied spatial fluctuations of the sky brightness using the NEP deep survey data obtained with AKARI IRC at two wavelength bands, 2.4 and 3.2 $\mu$m. Compared with the Monitor field of AKARI used in our previous study, the NEP deep field has larger areal coverage, enabling us to extend fluctuation analysis of the sky brightness at larger angular scales up to 1000$''$. We produced mosaic images for two bands and estimated spatial fluctuations using power spectrum analysis. We found that there is a residual fluctuation over the estimated shot noise even at larger angles than the angular scale of the Monitor field, which can hardly be explained by any known foreground components.

By using excess fluctuation of the NEP deep field, we confirm a blue stellar-like spectrum of excess fluctuation that was found in the previous study with the Monitor field and find the blue spectrum is still recognized even at larger angular scales. The excess fluctuation spectrum of the NEP deep field extends smoothly that of the Monitor field at angular scales of a few hundred arcseconds, and combination of the two results does not show any significant variation of fluctuation power at angular scales between a few hundred arcseconds and ~1000$''$. We show that the result of this study is consistent with the study of Spitzer at 3.6 $\mu$m. Such results could provide useful constraints for the study of background at the near-infrared wavelength bands.

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**Facility:** Akari (IRC)

REFERENCES

Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, Natur, 440, 1018
Arendt, R. G., & Dwek, E. 2003, ApJ, 585, 305

Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bevington, P. R., & Robinson, D. K. 1992, Data Reduction and Error Analysis for the Physical Sciences (2nd ed.; New York: McGraw-Hill)
Cambresy, L., Reach, W. T., Beichman, C. A., & Jarrett, T. H. 2001, ApJ, 555, 563
Chary, R., Cooray, A., & Sullivan, I. 2008, ApJ, 681, 53
Cooray, A., Bock, J. J., Keatín, B., Lange, A. E., & Matsushita, T. 2004, ApJ, 606, 611
Cooray, A., Gong, Y., Smidt, J., & Santos, M. G. 2012a, ApJ, 756, 92
Cooray, A., Smidt, J., de Bernardis, F., et al. 2012b, Natur, 490, 514
Dwek, E., & Arendt, R. G. 1998, ApJL, 508, L9
Essey, W., Kalashev, O. E., Kusenko, A., & Beacom, J. F. 2010, PhRvL, 104, 141102
Essey, W., & Kusenko, A. 2010, ApJ, 33, 81
Fernandez, E., Ilié, I. T., Komatsu, E., & Shapiro, P. R. 2012, ApJ, 750, 20
Fernandez, E., Komatsu, E., Ilié, I. T., & Shapiro, P. R. 2010, ApJ, 710, 1089
Gilmore, R. C., Somerville, R. S., Primack, J. R., & Domínguez, A. 2012, MNRAS, 422, 3189
Han, W., Lee, D.-H., Jeong, W.-S., et al. 2014, PASJ, 126, 853
Han, W., Lee, D.-H., Park, Y., et al. 2010, Proc. SPIE, 7731, 51
Hauser, M. G., Arendt, R. G., Kelsall, T., et al. 1998, ApJ, 508, 25
Helgason, K., Ricotti, M., & Kashlinsky, A. 2012, ApJL, 752, 113
H.E.S.S. Collaboration 2013, A&A, 550, A4
Hwang, N., Lee, M. G., Lee, H. M., et al. 2007, ApJS, 172, 583
Kashlinsky, A., Arendt, R. G., Ashley, M. L. N., et al. 2012, ApJ, 753, 63
Kashlinsky, A., Arendt, R. G., Gardner, J., Mather, J., & Moseley, S. H. 2004, ApJ, 609, 1
Kashlinsky, A., Arendt, R. G., Mather, J., & Moseley, S. H. 2007, ApJL, 654, L5
Kato, D., Ito, Y., Onaka, T., et al. 2012, AJ, 144, 179
Kawada, M., Baba, H., Barthel, P. D., et al. 2007, PASJ, 59, 389
Kelsall, T., Weiland, J. L., Franz, B. A., et al. 1998, ApJ, 508, 44
Kim, S. J., Lee, H. M., Matsushita, H., et al. 2012, A&A, 548, A29
Levenson, L. R., Wright, E. L., & Johnson, B. D. 2007, ApJ, 666, 34
Lorentz, R., Onaka, T., Ito, Y., et al. 2008, Akari IRC Data User Manual (version 1.4), http://www.ir.isas.jaxa.jp/ASTRO-F/Observation
Madau, P., & Silk, J. 2005, MNRAS, 359, L37
Maihara, T., Iwamuro, F., Tanabe, H., et al. 2001, PASJ, 53, 25
Markwardt, C. B. 2009, adass XVIII, 411, 251
Matsushita, H., Wada, T., Matsusra, S., et al. 2006, PASJ, 58, 673
Matsumoto, T., Matsusra, S., Murakami, H., et al. 2005, ApJ, 626, 31
Matsumoto, T., Seo, H. J., Jeong, W.-S., et al. 2011, ApJ, 742, 124 (Paper 1)
Meyer, M., Nau, M., Mazin, D., & Horns, D. 2012, ApJ, 752, 542
Miville-Deschênes, M.-A., & Lagache, G. 2005, ApJS, 157, 302
Murakami, H., Baba, H., Barthel, P. D., et al. 2007, PASJ, 59, 369
Oi, N., Matsushita, H., Murata, K., et al. 2014, A&A, 566, A60
Onaka, T., Matsushita, H., Wada, T., et al. 2007, PASJ, 59, 401
Pyo, J. H., Matsushita, T., Jeong, W.-S., & Matsusra, S. 2012, ApJ, 760, 102
Sullivan, I., Cooray, A., Chary, R.-R., et al. 2007, ApJ, 657, 37
Takagi, T., Matsushita, H., Goto, T., et al. 2012, A&A, 537, A24
Tody, D. 1986, Proc. SPIE, 627, 733
Tsumura, K., Matsumoto, T., Matsuura, S., et al. 2012, PASJ, 65, 121
Tsumura, K., & Wada, T. 2011, PASJ, 63, 755
Verdugo, E., Yamamura, I., & Pearson, C. 2007, AKARI/FIS Data User Manual (version 1.3), http://www.ir.isas.jaxa.jp/ASTRO-F/Observation
Wada, T., Matsushita, H., Oyabu, S., et al. 2008, PASJ, 60, 517
Wada, T., Oyabu, S., Ita, Y., et al. 2007, PASJ, 59, 515
Wright, E. L., & Reese, E. D. 2000, ApJ, 545, 43
Yue, B., Ferrara, A., Salvaterra, R., et al. 2013a, MNRAS, 431, 383
Yue, B., Ferrara, A., Salvaterra, R., et al. 2013b, MNRAS, 433, 1556
Zemcov, M., Smidt, J., Arau, T., et al. 2014, Sci, 346, 732