**Abstract**

We present **AREAcat**, an interactive online tool to compute the area mapped by recent catalogs that cover most of the sky, but not contiguously, such as the Galaxy Evolution Explorer (**GALEX**) ultraviolet (UV) source catalogs **GUVcat_AIS**. Constructed from $\lesssim 600$ million measurements by removing duplicate measurements of the same source in repeated observations, and sources in field rims, **GUVcat_AIS** contains photometry in FUV ($\lambda_{\text{eff}} \sim 1528\, \text{Å}$) and NUV ($\lambda_{\text{eff}} \sim 2310\, \text{Å}$) of $\sim 83$ million UV sources. When the surface density of a given class of objects is of interest, the actual area covered by the catalogs used in the source selection must be calculated, taking into account overlap among repeated observations and gaps between pointings. We developed a tool to calculate the area covered in any chosen region of the sky by **GUVcat**, as well as by the Sloan Digital Sky Survey data release 14 (SDSS DR14), the Panoramic Survey Telescope and Rapid Response System (PanSTARRS) PS1 3$\pi$, **Gaia** DR2, and their overlap with **GUVcat**. The desired sky region can be specified in either Galactic ($l$, $b$) or equatorial ($\alpha$, $\delta$) coordinates. **GUVcat** flags sources within the footprint of extended objects, such as nearby large galaxies or Galactic stellar clusters, where the photometry of individual point-like sources is often compromised by crowding or by the underlying galaxy light. For statistical studies of clean samples over large areas, the sources within such extended objects can be excluded using the appropriate **GUVcat** flags; the corresponding regions can then be excised from the area estimate in **AREAcat**.

**Key words:** catalogs – surveys – virtual observatory tools – galaxies: statistics – Galaxy: stellar content – stars: statistics – ultraviolet: stars

1. Introduction. Sky Surveys and the Need for an Area Calculation Tool

The ever-increasing scientific potential of modern sky surveys and the rapidly growing speed and power of database mining tools are characterizing much recent and current astrophysics, from studies of Milky Way stellar populations to the structure and history of the universe. Many surveys, especially from space-borne observatories, map the entire sky (e.g., **Gaia** data release 2 (DR2), **Gaia** collaboration et al. 2018; the Guide Star Catalog II (GSC2), Lasker et al. 2008; the Two Micron All-Sky Survey (2MASS), Skrutskie et al. 2006) or large contiguous portions (e.g., the Panoramic Survey Telescope and Rapid Response System (PanSTARRS), Chambers et al. 2016; the Sloan Digital Sky Survey (SDSS), Gunn et al. 1998), albeit in most cases with nonuniform depth (see, for example, the discussion in Lam et al. 2019 for PanSTARRS; in Bianchi et al. 2011b for GSC2).

Sky surveys have been, are being, and will be performed with increasing depth, resolution, and photometric quality across the entire electromagnetic spectrum, except for the ultraviolet (UV) range, which remains, to date and in the near future, confined to the data from the Galaxy Evolution Explorer (**GALEX**, Martin et al. 2005) in terms of sky surveys with modern detectors (Morrissey et al. 2007; Bianchi 2009, 2011, 2014, 2016; Bianchi et al. 2011a, 2014, 2017). During the **GALEX** mission, most of the effort was devoted to studies of nearby galaxies and star formation in the redshift $\lesssim 2$ universe, consistent with **GALEX**’s original science goal. At the same time, **GALEX** produced extensive, unprecedented sky surveys in two UV bands: FUV and NUV. However, due to limitations of budget for a Small Explorer (SMEX) class mission and of computer capabilities in the past decade, the data products (hosted at MAST3) have not been easy to exploit for statistical studies of large UV-selected source samples. **GALEX** database searches in MAST (both through the GalexView tool and the Casjobs query tool) return all source measurements in a given area, including repeated measurements when available, which are very useful, in particular, for studies focused on individual objects, but not for quickly selecting UV-source samples. To address a lack in the database of unique-source catalogs that facilitate mining and statistical studies of UV sources, **GUVcat** was produced by removing duplicate measurements in repeated observations ($\sim 57,000$ observations). In building **GUVcat**, incorrect associations of 1195 visits into 640 coadds that had been produced by the original pipeline were also cured; see Bianchi et al. (2017) for details and for description of other caveats. **GUVcat** supersedes earlier versions of unique UV-source catalogs constructed from previous data releases, **BCScat** (Bianchi et al. 2014), and the earlier catalogs of Bianchi et al. (2011a, 2011b). By retaining only one measurement for each UV source and by trimming the field edges that are plagued with artifacts, these catalogs, alone or matched with surveys at other wavelengths, allow us to extract selected UV-source samples effectively (e.g., Bianchi et al. 2011a, 2018a); they are also being used for a wide variety of
other applications (e.g., Barber et al. 2016; Monroe et al. 2016; Whitehorn et al. 2016; Battisti et al. 2017; Fantin et al. 2017; Aditya & Kanekar 2018; Brown 2018; Greco et al. 2018; Kong et al. 2018; Mahajan et al. 2018; Ruiz et al. 2018; Sun et al. 2018; Wolf et al. 2018; Popesso et al. 2019 to cite a few).

When the source density of the selected samples is of interest—for example, for comparison with models of stellar populations or galaxy counts—the effective sky coverage of the catalogs from which the source sample was selected must be estimated, accounting for both possible overlaps and gaps among the fields in different observations. An example in Figure 1 shows that accounting for gaps and overlaps in GALEX data can be complex and cannot always be easily accomplished using the list of field centers of the observations used to build the source catalog (the list is given in Table 4 of Bianchi et al. 2017). The need for a tool to compute the actual sky coverage was first addressed by Bianchi et al. (2011a) who developed an early version of the code. The code has now been expanded, improved, and embedded in a shell to make it available online for all users of our UV-source (Bianchi et al. 2014, 2017) and UV—optical matched catalogs (Bianchi 2018; L. Bianchi et al. 2019, in preparation), as well as of other major catalogs: SDSS, PanSTARRS, and Gaia.

2. The Sky Tessellation Grid. GUVcat Area Coverage

Figure 1 shows an example of a region near the Small Magellanic Cloud covered by several GALEX observations with partial overlaps as well as with some gaps. This region is an extreme case to illustrate that the area calculation can be complex, although overlapping fields are not very common in the All-Sky Imaging Survey (AIS, see Morrissey et al. 2007; Bianchi 2009; Bianchi et al. 2017). AREACat allows the user to select boundaries of a sky region, exemplified by the blue rectangle in Figure 1, and returns the area covered by GUVcat and other catalogs in the selected region.

The methodology is simple in principle. The sky is partitioned in small contiguous areas (bins), as tesserae of a mosaic covering the celestial sphere. Then, for GUVcat_AIS and for each additional catalog considered (or matched catalog), a flag maps whether each tessera is or is not covered by that catalog. Once the user specifies a region in the sky (or the whole sky), the areas of all tesserae that fall within that region and are covered by a given catalog or by matched catalogs are added up, yielding the total area covered. Unlike the often used HEALPix sky partition, which is convenient for some database applications, such as extracting source samples by coordinate searches, we adopted a sky tessellation design that is simpler and more efficient for the present purpose. The celestial sphere is divided in Galactic latitude strips the width of the bin size, and each strip is divided into a number of bins such to make the bin width in longitude as close as possible to the chosen tessellation step.5 As a result, centers of the bins are aligned along Galactic parallels, with contiguous parallels being spaced by the bin size. Along each individual parallel, the bin centers are equally spaced in longitude; but they are not aligned along longitude circles, because each 360° parallel circle is divided into the approximate number of bins such that the actual bin width as close as possible to the nominal bin size. Therefore, bin areas are not exactly identical at different latitudes, as bin widths in longitude are not precisely 0°1 (or 0°05), but the exact area of each bin is recorded in the tessellation map.

Arranging the grid along latitude and longitude facilitates most potential applications of the catalogs, such as our own goals to build hot-star density and extinction maps across the Milky Way, for comparison with Milky Way models (e.g., Bianchi et al. 2011a; Bianchi 2018) and allows very fast calculations. An advantage with respect to HEALPix-based maps may also be in precision, since source density must often be examined as a function of Galactic latitude, for obvious reasons in the case of Milky Way stellar populations, but also for extragalactic sources, to account for the Milky Way foreground extinction, which is especially relevant when UV data are involved. Tessellation bins aligned along parallels can reduce the number of bins that extend across the selected-region boundary and contribute to the uncertainty of the area estimate (see Section 4).

The center of each tessellation bin is stored in the map with α, δ (R.A., decl.) values in addition to l, b, so in the end, the calculation proceeds equally fast for either coordinate system, equatorial or Galactic. Figures 2 and 3 illustrate the methodology.

A new and notable feature of GUVcat is the addition of flags indicating whether a source falls within the footprint of extended objects, such as nearby galaxies or crowded stellar clusters. Inside these footprints, detection and photometry of sources, even of foreground point-like sources, are often significantly compromised by the bright and complex background light of the extended objects, causing point-like sources to be possibly missed or integrated into one extended source, but also causing significant mismatches to occur between sources detected in the two images, FUV and NUV. Such limitations in source extraction can cause counter-intuitive and nonphysical situations. For example, an extended nearby galaxy may have fewer source detections in the center than in its periphery, or a globular cluster may have more FUV sources listed in the GALEX database than NUV sources, because the few, sparse FUV sources are resolved by the pipeline, while the numerous, crowded NUV sources are

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4 https://healpix.jpl.nasa.gov/

5 Current options for bin size are 0°1 or 0°05.
integrated into one large source; see Figures 5(c)–(d) and 5(a)–(b) of Bianchi et al. (2017) for illustrative examples. Even after using source-extraction parameters to select point-like sources, it is, therefore, important for analysis of samples of foreground or background objects to exclude the UV sources within the footprint of the most complicated extended objects. Such critical “sample cleaning” can be easily accomplished using the tags “INLARGEOBJ” and “LARGEOBJSIZE” provided in GUVcat. The second tag gives the size of the extended object; therefore, the user can choose to eliminate only sources that fall within the footprint of galaxies or clusters larger than a given size, considering that only the very large ones pose significant problems and tuning the choice according to the sample extent and the purpose of the analysis. If sources within the footprint of extended objects are discarded from a selected sample, the covered area must also account for the “holes” in the catalog corresponding to those extended objects whose footprints are excluded. This option is available in AREAcat, making it—together with GUVcat—uniquely useful for accurate selection of specific classes of UV sources and estimates of source density. The option is illustrated by the sketch in Figure 3.

An important caveat: the current default grid step in AREAcat is 0°1 (0°.05 is also available); therefore, it is not advisable to exclude portions of sky smaller than a few ×6', because the uncertainty in the area estimate due to the resulting “holes” may offset the benefit of excluding some sources (see Section 4), and objects less extended than several arcminutes do not significantly affect the source samples. To guide the choice of what minimum size for the extended objects to be excluded is most beneficial for a given purpose, one can examine finding charts of the extended objects flagged in GUVcat, with GUVcat UV sources overlaid, which are provided at the author’s uvsy website serving GUVcat.6 Over the entire sky, the extended galaxies and stellar clusters considered for the “INLARGEOBJ” flagging (larger than 1’) amount to 445 square degrees, with little difference (less than 0.2%) between using bin size = 0°1 (444.083 square degrees) or bin size = 0°.05 (444.903 square degrees). Of these, ~152 square degrees are in the GUVcat_AIS_055 footprint. The extended objects larger than 30' cover a total area of 363 square degrees (362.797/363.077 square degrees for bin size = 0°1/0°.05) over the whole sky, of which ~133 square degrees are in the GUVcat_AIS_055 footprint. Therefore, AREAcat is an essential tool when large areas are considered. Of course, the area coverage within a single field or a few

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Figure 2. Cartoon to illustrate the tessellation and the area calculation. The grid represents the tessellation of 0°1-size bins along Galactic latitude and longitude, although in the actual grid the bin centers are not exactly aligned in longitude, because in order to keep the bin size constant, fewer bins are needed to cover a 360° parallel circle at high Galactic latitudes than at low latitudes. The red “plus” is the field center. The red dashed circle represents a GALEX field (∼1°2 diameter) and the solid circle represents the 1° inner portion from which sources of GUVcat_AIS_050 are retained. The bins whose centers (dots) are inside the red solid circle are counted for the total area (shaded bins). Bins not entirely included in the circle are missed if the bin center is outside the circle, whereas the entire bin area is included if the bin center falls inside the circle. Statistically, the lack or excess of area from edge bins compensate each other. The error in the result is discussed in Section 4.
fields can (and should) instead be estimated with a simple geometrical calculation, yielding an exact result.

3. Coverage of Matched Catalogs and Other Catalogs and Surveys: SDSS, PanSTARRS, and Gaia

Many science applications of the UV-source catalogs are accomplished by matching them to surveys at other wavelengths, mostly in the optical range. The most extensive modern optical survey available since the time of the early GALEX catalogs, and until PanSTARRS PS1 was released, was SDSS (Gunn et al. 1998). By matching the GALEX FUV and NUV magnitudes to the SDSS optical magnitudes $u$, $g$, $r$, $i$, and $z$, classes of astrophysical sources that are elusive in optical surveys alone can be easily identified, such as for example hot white dwarfs (e.g., Bianchi et al. 2005, 2007, 2011a, 2018a; Bianchi 2009), or classes of sources in parameter ranges to which optical wavelengths are insensitive. New subclasses of objects can also uniquely stand out or be discovered (e.g., Bianchi et al. 2009; Hutchings & Bianchi 2010a, 2010b; Smith et al. 2014). While the multi-wavelength photometric spectral energy distribution enables identification of classes of sources or selection of sources in given parameters ranges, interpretation of these samples often requires one to compute the source density for comparison with model predictions. Therefore, the area actually covered by the catalog or the matched catalogs from which the sample has been extracted must be estimated.

3.1. SDSS DR14

For matched GALEXxSDSS catalogs, in principle, after the area of the UV survey has been mapped, one could use the SDSS online Footprint tool to find out what portion of the UV survey is also covered by SDSS. However, since producing our first matched catalogs, we have found that the SDSS Footprint tool may return false positives and false negatives (Bianchi et al. 2011a), yielding in this case an incorrect area estimate, which propagates on source density estimates. We do not know the reason for the occasional incorrect results from the SDSS Footprint tool, but we surmise that the footprint may be generated with the nominal observation pointings, while the released photometric catalog will only contain fields that have been actually observed and processed, and the processing yielded a satisfactory quality level. Regardless what causes the discrepancy, we obviously must include in the area integration all and only the portions of the sky where there are actually SDSS sources in the SDSS catalog, and we consider not covered those bins entirely devoid of sources. AREAcat returns two results for the area: one is calculated using the output from the SDSS Footprint query for our tessellation bins, and one
using our own footprint mapping, based on queries that search whether there are any SDSS sources within a radius half of the bin size; therefore, statistically (scaling by the area), the counts in the cone are $\sim$80% of the counts in the entire, approximately square bin.

We performed the ConeSearch query to count sources within a radius half of the bin size; therefore, statistically (scaling by the area), the counts in the cone are $\sim$80% of the counts in the entire, approximately square bin.

AREAcat performs area calculations with the two methods for both the SDSS DR14 alone and the matched GUVcatxSDSS DR14 coverage. For the smaller bin size offered in our maps, $0.05^\circ$, the maximum number of SDSS DR14 sources in a $0.05^\circ$ diameter cone is 4381, and the mean in the whole SDSS catalog is 58.6 sources per bin. Figure 4(left) shows the statistical distribution of source counts per bin. Over the whole sky, there are 5,886,859 bins (size $= 0.05^\circ$) containing SDSS sources according to our ConeSearch query, but 5,889,398 bins are deemed positive from the SDSS Footprint query tool; the difference (2539 bins) amounts to a $\sim$6.4 square degrees total area difference. Therefore, the area computed using the results from our ConeSearch map is preferable.

We point out an important difference with respect to the GUVcat area calculations. In the case of GALEX GUVcat, bins partially included in the observation’s field of view and in the considered region boundaries may be either included or excluded from the area integration, depending on whether their center falls inside or outside the boundary. Therefore, the lacking and excess areas from individual bins along boundaries compensate each other statistically. Instead, for SDSS coverage maps based on source counts, a bin that contains any number of SDSS sources is always included in the footprint, and its whole area is added. Therefore, the uncertainty in this case is not a statistical fluctuation; the value may be instead an upper limit, and how close it will be to the actual area will depend on how many “border bins” fall into the chosen region (we will return to this point in Section 4). Nonetheless, it seems to be the closest to the real value that can be possibly obtained, given that—over the whole sky—the area from our source-counts mapping is smaller than that obtained from the SDSS Footprint tool (Table 1), using the $0.05^\circ$ bin size grid. In some sky regions, however, occasionally the area resulting from SDSS source-counts mapping is larger than that from the SDSS Footprint output, implying either false negatives from the Footprint output or a slight excess estimate (e.g., many bins along a SDSS field border) from the source-counts mapping. Both values are returned from AREAcat; a conspicuous difference may indicate the need for an ad hoc investigation of the desired region. We also stress that, in this case, the calculation with the smaller bin size is preferable. In fact, if the difference between results from source-counts mapping versus SDSS Footprint is only 6.4 square degrees in the whole sky using the finer grid, while using bin size = $0.01^\circ$ yields a larger coverage of the source-counts-based maps by over 200 square degrees over the whole sky. This cannot be simply interpreted as accumulated excess from the bins along field borders, because at Galactic latitudes $\geq 60^\circ$, the area from source-counts mapping is smaller than that from the Footprint map, implying some false positives from the Footprint map. The discrepancy increases toward southern latitudes where the SDSS coverage is minimal, as shown in Figure 1 of Bianchi et al. (2014).

### 3.2. Gaia DR2

Gaia covers the whole sky, accumulating scans with a pattern that results in progressive completeness as the survey continues. As we have done for the SDSS, we have counted the Gaia DR2 sources within cones of $0.1^\circ$ and $0.05^\circ$ diameter centered on each center of our tessellation bins, as a test for completeness. Only six $0.1^\circ$-size bins have no Gaia sources, but as many as 17,687 $0.05^\circ$-size bins have zero sources, which adds up to a total area of $\sim$408 square degrees in the whole sky. If these were true gaps in coverage, the number of empty

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$^5$ We performed the ConeSearch query to count sources within a radius half of the bin size; therefore, statistically (scaling by the area), the counts in the cone are $\sim$80% of the counts in the entire, approximately square bin.
| $b$ Range | GUVCat AIS_055 | GUVCat AIS_050 x SDSS DR14 | GUVCat AIS_050 x SDSS DR14 | SDSS DR14 | GUVCat AIS_055 x PS1 | GUVCat AIS_050 x PS1 | PanSTARRS PS1 | BCScat | BCScat | BCScat X SDSS DR10 |
|-----------|---------------|----------------------------|----------------------------|-----------|----------------|----------------|--------------|--------|--------|------------------|
| -90 .. 90 | 24788.0       | 22125.0                    | 11097.6                    | 11062.2   | 9934.5         | 9902.9         | 14171.5      | 14271.6 | 19347.8 | 19614.0         |
|           | 24654.8       | 22099.2                    | 11073.3                    | 11037.5   | 9913.2         | 9881.8         | 14665.3      | 14670.4 | 19310.5 | 19576.2         |
| 80 .. 90  | 271.3         | 243.6                      | 213.0                      | 217.3     | 243.3          | 243.6          | 231.2        | 231.3   | 259.6   | 259.6            |
|           | 259.6         | 233.3                      | 259.3                      | 259.6     | 231.3          | 231.3          | 292.3        | 292.6   | 233.3   | 233.3            |
| 70 .. 90  | 1096.5        | 986.4                      | 1095.2                      | 1096.4    | 986.4          | 986.4          | 1242.5       | 1243.9  | 986.4   | 986.4            |
|           | 1084.4        | 975.9                      | 1083.6                      | 1084.4    | 975.9          | 975.9          | 1222.7       | 1223.9  | 975.9   | 975.9            |
| 60 .. 90  | 2323.6        | 2087.4                      | 2312.6                      | 2323.2    | 2087.3         | 2087.3         | 2760.7       | 2763.2  | 2087.4  | 2087.4          |
|           | 2311.4        | 2076.9                      | 2309.7                      | 2311.2    | 2076.8         | 2076.8         | 2740.9       | 2743.2  | 2076.9  | 2076.9          |
| 50 .. 90  | 4014.7        | 3601.6                      | 3773.7                      | 3774.8    | 3853.7         | 3886.6         | 4554.3       | 4547.4  | 4014.5  | 4014.5          |
|           | 4002.9        | 3591.6                      | 3761.9                      | 3762.6    | 3752.6         | 3767.1         | 4525.4       | 4524.7  | 4002.6  | 4002.6          |
| 40 .. 90  | 6128.9        | 5496.6                      | 5161.5                      | 5154.9    | 6268.5         | 6266.2         | 6216.9       | 6215.5  | 6128.5  | 6128.5          |
|           | 6116.4        | 5486.1                      | 5149.6                      | 5147.4    | 6181.6         | 6186.1         | 6196.9       | 6195.2  | 6116.6  | 6116.6          |
| 30 .. 90  | 8532.5        | 7650.7                      | 6343.7                      | 6363.8    | 6588.8         | 6589.5         | 7648.8       | 7641.2  | 6588.9  | 6589.6          |
|           | 8511.9        | 7634.0                      | 6324.7                      | 6317.2    | 6571.9         | 6566.2         | 7671.2       | 7609.4  | 6409.6  | 6546.7          |
| 20 .. 90  | 10814.8       | 9689.4                      | 7010.0                      | 6995.6    | 6282.6         | 6266.9         | 8554.9       | 8535.2  | 9235.2  | 9315.3          |
|           | 10793.6       | 9667.9                      | 6991.1                      | 6976.5    | 6260.0         | 6252.9         | 8523.4       | 8503.4  | 9218.2  | 9298.4          |
| 10 .. 90  | 12577.1       | 11325.8                     | 7330.9                      | 7312.6    | 6565.9         | 6549.8         | 9096.0       | 9084.3  | 11713.8 | 11819.0         |
|           | 12551.7       | 11215.5                     | 7311.8                      | 7293.5    | 6549.2         | 6532.9         | 9036.8       | 9016.0  | 11691.2 | 11796.4         |
| 0 .. 90   | 12997.1       | 11580.9                     | 7957.9                      | 7832.4    | 6622.2         | 6610.2         | 9429.4       | 9444.9  | 12074.1 | 12078.0         |
|           | 12971.6       | 11580.4                     | 7736.6                      | 7632.3    | 6605.4         | 6593.4         | 9395.8       | 9410.4  | 12051.8 | 12157.3         |

Notes:
- For each latitude range, the first row gives the total area covered, the second row gives the area excluding extended objects larger than 30 arcmin (see tag LARGEOBJSIZE in GUVCat (Bianchi et al., 2017), and Section 2). We used bin size = 0.05 for all columns except for the last three concerning BCScat, for which we used bin size = 0.1.
- The first number is the area calculated using our mapping from the source search in each tessellation bin; the second is calculated from the SDSS FootPrint server (see Section 3.1).

Table 1  Areas Covered by Major Surveys and Catalogs in Representative Sky Regions
0.1-size bins should be about four times lower, i.e., >4400, while it is only 6 (0.06 square degrees total). Therefore, we interpret the high number of empty 0.05-size bins as statistical fluctuations around a very low source density and not as coverage gaps. This conclusion is supported by the distribution of number of sources per bin shown in Figure 4(right). Given the much higher spatial resolution of Gaia and its rather brighter limit compared with SDSS or PanSTARRS, we can expect to see many more sources in crowded regions thanks to the higher resolution, but fewer sources in sparse regions due to the higher brightness limits. The Gaia source counts in 0.05 diameter circles range from 1 to 4360, with an average of 81, but the number of bins with source counts of a few are the vast majority. Therefore, while for GALEX, SDSS, and PanSTARRS, an area calculation with the smaller-bin map will be more accurate, our statistics suggests that using a 0.1 bin size for Gaia is preferable for source-count mapping, but, in fact, that it is safer to assume that Gaia sky coverage has no actual gaps. AREAcat returns results both using the bin map from the ConeSearch counts, and assuming that there are no gaps in sky coverage; the latter is to be used for Gaia, given the false negatives caused by the low surface density of sources, as explained above. A discrepancy between the two results, in this case, may indicate a region of very low source density in DR2 rather than a gap in coverage.

3.3. PanSTARRS PS1 3π

The nominal sky coverage of PanSTARRS PS1 3π survey is essentially the whole sky north of δ = −30° (more than twice as large as SDSS), and the survey is slightly deeper than SDSS in some bands. Therefore, it offers a great advantage with respect to SDSS for crossmatching GUVcat UV sources with an optical database. We performed a ConeSearch, counting the PanSTARRS PS1 3π sources in each tessellation bin of our sky map, as was done for SDSS and Gaia in the previous sections. The result shows that the actual photometric catalog extends slightly below δ = −30°. For the selected region of the sky, AREAcat returns results both using the bin map from the ConeSearch-based coverage map, as well as using a nominal cut at δ ≥ −30°; the latter is useful in case such a cut is applied to the source sample. The total area and the area covered in latitude slices are given in Table 1, as for the other catalogs. The average source counts in 0.1-diameter circles around our bin centers range from 1 to 31,161, with an average of 2612 sources/bin. The area resulting from the source-counts-based catalog, as i.e., adding all bins that contain sources) is 32,192 square degrees. North of δ = −30°, only one 0.1-size bin contains zero sources. Therefore, we can confirm that the catalog is essentially complete in sky coverage, if not homogeneous in depth, north of δ ∼ −30°.

In more detail, in the 0.05-size bin grid, there are 182,168 bins with no PanSTARRS sources north of δ = −30°; all of these are between −30 and −28.5; 30°, 56,831 are north of δ = −29°; no 0.05-size bin north of δ = −28.5 is empty. The source counts in the 0.05-size bins that are not empty range from 1 to 11,757, with a mean of 670 sources/bin. Therefore, some of the empty bins may also be due to statistical fluctuations in areas of low source density, although this is less likely than it is for surveys, considering the larger number of sources. The much higher number of source counts, with respect to SDSS, is due to the repeated observations in the PanSTARRS catalog. Our present purpose is not to estimate source density, but to count as many sources as possible in order to see whether a tessellation bin is included in the survey. Therefore, the catalog of mean measurements from individual exposures was used, rather than the stacked catalog, which has about five times fewer sources.

4. Accuracy of the Area Calculation

As illustrated in Figures 2 and 3, tesserae of the sky tessellation along the edges of GALEX fields or along boundaries of a selected region, may be partly covered by the catalog, each bin causing either a slight excess or lack of area integration according to whether the bin center is inside or outside the boundary. As can be also gathered visually from the drawings in Figures 2 and 3, such situations tend to compensate each other statistically, the more so the larger the area considered and the smaller the bin size of the tessellation. Bianchi et al. (2011a), who used a first version of this code, have made extensive simulations by wiggling the grid bin centers in both longitude and latitude and found errors less than 1 square degree for the entire sky and for subregions. AREAcat is greatly improved with respect to the early version of the code and is based on a more homogeneously distributed grid; therefore, the previous error assessment can be considered conservative.

Also, in the case of partly included bins along the edges of GALEX fields, for bins whose centers are just inside the boundary, the area overestimate can be at most half of the bin area; likewise, no more than half of the bin area will be missed if a bin center is just outside the border. For our SDSS or PanSTARRS sky mapping based on source counts in each bin, however, any partly covered bin along edges of the observed fields (that is not devoid of sources) would always cause an overestimate in coverage, as pointed out in Section 3.1, because its entire area is included even if the bin contains only one source, in which case it may lie mostly outside the border, and the area excess may amount up to almost the entire bin, unlike the GALEX case described above. Note that such uncertainties can possibly arise only from bins along edges of observation fields; in regions of large contiguous coverage, there are likely no bins affected, thus no such source of uncertainty.

Then, in the integration of areas from all bins included in a selected region, the bins along the selected-region boundaries will—in all cases—compensate each other statistically, with some bins centers falling just inside and some just outside the boundary. For SDSS, results from source-counts mapping are often more accurate than results based on the SDSS Footprint mapping; the uncertainty varies according to the chosen sky region, and the finer grid is recommended, as explained in Section 3.1. When the two results do not differ significantly, the Footprint-based mapping may have no false negatives or positives. For Gaia, and for PanSTARRS north of δ ∼ −29°, as mentioned earlier, one can assume no gaps in sky coverage; for PanSTARRS south of δ ∼ −29°, our source-counts-based maps may be the only ones currently available.

For all the individual and matched catalogs included in our mapping, Table 1 gives the total area covered and the area in progressive latitude ranges. Except for BCScat, the areas are computed with the 0.05 bin size grid. In Table 2, we give the difference in area results using bin size = 0.05 versus bin size = 0.10 for all cases where we give areas in Table 1. These differences show, as mentioned earlier, that errors from partially included bins along the edges statistically compensate
Table 2

Difference (%) between Areas Calculated with Bin Size = 0'05 vs. 0'1

| b Range | GUVCat_AIS_055 x SDSS DR14 | GUVCat_AIS_055 x SDSS DR14b | GUVCat_AIS_050 x SDSS DR14 | GUVCat_AIS_055 x PS1 3σ | GUVCat_AIS_050 x PS1 3σ | PanSTARRS PS1 3σ |
|---------|----------------------------|-------------------------------|-----------------------------|-------------------------|-------------------------|-------------------|
| -90 .. 90 | -0.01 -0.00 -1.15 .. -0.01 -1.14 .. -0.00 -1.56 .. -0.02 -5.06 .. -0.00 -5.03 .. -0.00 -5.30 .. -0.00 |
| 80 .. 90 | 0.00 0.00 -0.08 .. 0.00 -0.10 .. 0.00 0.00 .. 0.00 0.04 .. 0.04 -0.04 .. -0.04 0.00 .. 0.00 |
| 70 .. 90 | 0.00 0.04 -0.09 .. 0.04 -0.10 .. 0.00 0.04 .. 0.04 -0.04 .. -0.04 0.00 .. 0.00 |
| 60 .. 90 | -0.01 0.03 -0.06 .. 0.00 -0.07 .. 0.00 -0.11 .. -0.01 -0.12 .. -0.00 -0.00 .. -0.00 -0.01 .. -0.01 |
| 50 .. 90 | 0.00 -0.01 -0.10 .. 0.00 -0.12 .. -0.01 -0.12 .. -0.00 -0.00 .. -0.00 -0.01 .. -0.01 |
| 40 .. 90 | -0.01 -0.01 -0.27 .. -0.00 -0.29 .. -0.00 -0.29 .. -0.00 -0.00 .. -0.00 -0.01 .. -0.01 |
| 30 .. 90 | 0.00 -0.00 -0.42 .. -0.00 -0.45 .. -0.00 -1.07 .. -0.01 -1.07 .. -0.01 -1.06 .. -0.00 -1.00 .. -0.00 |
| 20 .. 90 | -0.01 0.02 -0.61 .. 0.00 -0.71 .. -0.00 -2.42 .. -0.01 -2.42 .. -0.01 -2.40 .. -0.01 -2.51 .. -0.00 |
| 10 .. 90 | 0.00 -0.01 -0.79 .. -0.00 -0.95 .. 0.00 -2.76 .. -0.02 -2.76 .. -0.01 -2.72 .. -0.01 2.97 .. -0.00 |
| 0 .. 90 | -0.01 -0.01 -0.83 .. -0.00 -1.20 .. -0.01 -2.77 .. -0.01 -2.77 .. -0.01 -2.73 .. -0.01 -2.98 .. -0.00 |
| -90 .. -80 | 0.00 0.16 -7.11 .. 5.3 -6.91 .. 0.00 -6.99 .. -0.00 -6.99 .. -0.00 -35.86 .. 0.05 -35.80 .. -0.00 -35.80 .. -0.00 |
| -90 .. -70 | 0.00 0.53 -6.91 .. 0.00 -6.69 .. 0.00 -6.69 .. -0.00 -35.68 .. 0.05 -35.63 .. 0.00 -35.65 .. 0.05 |
| -90 .. -60 | -0.02 0.21 -4.50 .. 0.16 -4.80 .. 0.12 -4.80 .. 0.12 -24.66 .. -0.02 -24.51 .. -0.17 -24.80 .. -0.01 |
| -90 .. -50 | 0.00 0.06 -2.26 .. 0.05 -2.55 .. 0.06 -2.55 .. 0.03 -18.16 .. -0.01 -17.98 .. -0.09 -19.18 .. -0.00 |
| -90 .. -40 | -0.03 0.05 -2.26 .. 0.05 -2.55 .. 0.06 -2.55 .. 0.03 -18.10 .. -0.01 -17.92 .. -0.09 -18.93 .. -0.00 |
| -90 .. -30 | 0.00 0.03 -1.42 .. 0.02 -1.42 .. 0.02 -1.42 .. 0.02 -14.34 .. -0.01 -14.20 .. -0.06 -15.44 .. -0.00 |
| -90 .. -20 | -0.03 0.03 -1.42 .. 0.02 -1.42 .. 0.02 -1.42 .. 0.02 -14.34 .. -0.01 -14.20 .. -0.06 -15.44 .. -0.00 |
| -90 .. -10 | 0.00 0.02 -1.29 .. 0.01 -1.25 .. 0.00 -1.25 .. 0.00 -12.32 .. 0.00 -12.23 .. 0.02 -13.02 .. -0.00 |
| -90 .. 0 | -0.02 0.02 -1.29 .. -0.01 -1.25 .. -0.01 -1.25 .. -0.00 -12.32 .. -0.00 -12.23 .. -0.02 12.85 .. -0.00 |
| -90 .. 10 | 0.00 0.01 -1.40 .. -0.01 -1.40 .. -0.01 -1.41 .. 0.02 -11.10 .. 0.00 -11.03 .. -0.02 11.30 .. -0.00 |
| -90 .. 20 | -0.01 0.01 -1.40 .. -0.01 -1.41 .. -0.01 -1.41 .. -0.01 -11.03 .. -0.00 -11.03 .. -0.02 -11.19 .. -0.00 |
| -90 .. 30 | 0.00 0.01 -1.51 .. 0.01 -1.55 .. -0.02 -1.61 .. -0.00 -9.78 .. -0.01 -9.74 .. 0.00 -10.13 .. -0.00 |
| -90 .. 40 | -0.01 0.01 -1.51 .. 0.01 -1.54 .. -0.02 -1.61 .. -0.00 -9.73 .. -0.01 -9.70 .. 0.00 -10.08 .. -0.00 |
| -90 .. 50 | 0.00 0.02 -1.66 .. 0.02 -1.69 .. -0.02 -1.94 .. -0.01 -8.92 .. -0.01 -8.90 .. 0.00 -9.17 .. -0.00 |
| -90 .. 60 | -0.02 0.01 -1.66 .. 0.02 -1.69 .. -0.02 -1.93 .. -0.01 -8.73 .. -0.01 -8.72 .. 0.00 -8.82 .. -0.00 |
| -90 .. 70 | -0.02 0.00 -1.71 .. -0.01 -1.74 .. -0.02 -2.18 .. -0.03 -8.65 .. 0.01 -8.64 .. 0.00 -8.50 .. -0.00 |
| -90 .. 80 | 0.00 0.00 -1.71 .. 0.01 -1.74 .. -0.02 -2.18 .. -0.03 -8.47 .. 0.01 -8.46 .. 0.00 -8.01 .. 0.00 |

Notes.

a As in Table 1, for each sky region, the first row refers to the total area, while in the second row extended objects larger than 30′ are excluded. A negative sign means that the result for bin size = 0'05 is smaller than that using bin size = 0'10.

b As in Table 1, the first number refers to areas mapped from the source search in each tessellation bin, the second refers to areas calculated from the SDSS FootPrint server (see Section 3.1).

c For PanSTARRS PS1 3σ survey, as in Table 1, the first value refers to the total sky area north of δ ≥ −30°, the second refers to areas calculated from source counts in the tessellation bins (Section 3.3). Differences arise in the regions that include several bins along the survey edge.
each other, more so the larger the area considered and the finer the grid, as can be seen for GUVcat cases where the finer grid gives more accurate results. Even for the smallest areas (the least covered regions), the difference is less than 0.2%. For SDSS or PanSTARRS source-counts-based maps, where partially included bins along the edges of the observed fields always cause a slight overestimate of the area, the difference increases for larger regions (1.1% for the whole sky (the estimated area from the $0.05\text{-step}$ tessellation being smaller as expected) and for regions with very little coverage where it reaches $\sim7\%$ in one case, but it is mostly less or much less than 1% in the regions of good coverage (essentially the northern sky). For all these cases, the finer grid mapping gives better results, at the expense of computing time, as already noted. Since Gaia covers the entire sky with no gaps, the area error will simply propagate from the GUVcat mapping when matched catalogs are used, and of course, an exact geometrical calculation is possible and preferable if the Gaia catalog alone is used.

For an overview of the sky coverage of SDSS and PanSTARRS in Galactic coordinates, see Figure 1 of Bianchi et al. (2014). For PanSTARRS, as reported in Section 3.3, there are no gaps in coverage for decl. north of $-28.5\degree$, and the catalog extends south of $\delta = -30\degree$.

The approximation due only to the integration of the tessellation tesserae was also tested for a hypothetical catalog covering the whole sky, by comparison with geometrical calculations of the entire sphere and of various spherical portions; it is always much better than 1%.

As in any tool based on a sky tessellation, one must always keep in mind the effect of the discrete bin size, i.e., the spacing between consecutive bins, on each specific application. In our partition, bins are aligned along parallel circles of Galactic latitude (Section 2), the $n$th circle being at latitude $[\delta] = 90\degree - (\text{bin size}/2\degree) - (n \times \text{bin size})$. Therefore, for example, the closest parallels of bin centers for $b = 60\degree$ are at latitudes of $59.995$ and $60.005$ for the bin-size of $0.1\degree$ grid. The area of GUVcatAIS_055 between $b = 90\degree$ and $60\degree$ is $2323.6013$ square degrees, and AREACat will return the same value if the lower $b$ limit is changed around $60\degree$ by less than half bin size, e.g., $b \geq 59.951$. But for a lower limit of $b = 59.949$, AREACat returns an area of $2338.1790$ square degrees, because the entire next parallel circle is included in the integration. Because of our tessellation geometry, typical boundary values of round latitude numbers, such as $60\degree$ in our example, will, therefore, return a very realistic value, as they are in between two circles of bin centers. If, instead, a region boundary in latitude is chosen exactly along one of the parallel circles of our grid bin centers, one can easily compute the area both including and excluding that circle by slightly varying the boundary; the middle value of the two results will approximate the actual area well as it would include half areas for the bins along the boundary parallel circle. This is an advantage of our mapping with respect to a HEALpix partition, when regions are studied as a function of Galactic latitude.

5. Summary and Perspectives

AREACat can be used online at http://dolomiti.pha.jhu.edu/uvsky/area/AREACat.php. It currently offers the options to compute the area coverage of previous versions of the GALEX UV-source catalog and matched GALEXXSDSS catalogs BCSCat (Bianchi et al. 2014), although the BCSCat_AIS catalog is now superseded by GUVcat_AIS, which should be used instead for the reasons explained by Bianchi et al. (2017).

The sky region of interest can be selected in either the Galactic $l$, $b$ or the Equatorial $\alpha$, $\delta$ coordinate system. As mentioned in Section 2, AREACat offers the option to exclude the footprint of large galaxies or clusters, if the GUVcat sources that fall in those footprints are excluded from the sample. A minimum size of the extended objects to be excised from the area calculation can be specified, as can be done with GUVcat tags to eliminate the corresponding UV sources. This minimum size limit must be considered carefully and must always be much larger than the bin size to avoid introducing an unnecessary source of uncertainty in the result (Section 2).

We stress again that, due to the bin size of $0.1\degree$ or $0.05\degree$, the tool is necessary and the result is accurate when large areas are considered, such as more than a few GALEX fields or several times the bin size. For smaller areas, an exact analytical calculation should be performed. For ease of studies concerning samples extracted over large portions of the sky, and to appreciate the coverage of various surveys at a glance, Table 1 gives the area covered by major catalogs over the whole sky and in progressive latitude ranges.

Regarding future perspectives, AREACat might be updated with more catalogs in the future, if relevant. Of course, for any catalog that covers the whole sky with no gaps (e.g., OCS2, 2MASS), the area covered by the match with GUVcat will just be the area covered by GUVcat. We will also consider the possibility of having mirror versions hosted at Virtual Observatory sites, as well as implementing additional options to select the sky region (e.g., a circle of a chosen radius rather than $l$, $b$ or $\alpha$, $\delta$ limits).

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References

Abolfathi, B., Aguado, D. S., Aguilar, G., et al. 2018, ApJS, 235, 42
Aditya, J. N. H. S., & Kanekar, N. 2018, MNRAS, 481, 1578
Barber, S., Belardi, C., Kilic, M., & Gianninas, A. 2016, MNRAS, 459, 1415
Battisti, A. J., Calzetti, D., & Chary, R.-R. 2017, ApJ, 840, 109
Bianchi, L. 2009, Ap&SS, 320, 11
Bianchi, L. 2011, Ap&SS, 335, 51
Bianchi, L. 2014, Ap&SS, 354, 103
Bianchi, L. 2016, Astrophysics and Space Science Library, 435, 52, https://link.springer.com/book/10.1007%2F978-3-319-31006-0
Bianchi, L. 2018, in Proc. STScI Symp. The XXI Century H-R Diagram: The Power of Precision Photometry (Baltimore, MD: STScI), 63, http://www.stsci.edu/institute/conference/spring2018/booklet.pdf
Bianchi, L., Conti, A., & Shiao, B. 2014, AdSpR, 53, 900
Bianchi, L., Efremova, B., Herald, J., et al. 2011a, MNRAS, 411, 2770
Bianchi, L., Herald, J., Efremova, B. et al. 2011b, Ap&SS, 335, 161

\[ A_{\text{area}} = \text{sum of areas of bins overlapping } \bigcup \text{GUVcat} \]
