

# Whitespace Evaluation Software (WEST) and its applications to whitespace in Canada and Australia

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**Abstract**—Spectrum whitespaces and dynamic spectrum sharing have become important and interesting topics in recent years. The USA authorized the use of TV whitespaces in 2008 and the UK and Canada followed suit in early 2015. In light of the PCAST report of 2012, additional bands are being evaluated for spectrum sharing in the USA and abroad.

With the increasing momentum of spectrum whitespaces, it is more important than ever to understand the consequences of regulatory decisions. For example, what is the effect of increasing the separation distance from 10km to 15km? Regulators need the ability to understand tradeoffs like this so that they can make informed decisions based on *actual*, not hypothetical or supposed, impact.

Despite the clear need, data-driven analyses appear to be quite rare among regulators, industry members, and researchers alike. Although the data is often freely available, employing it can be an onerous task. In order to reduce this barrier, we have created an open-source software package, WEST, that quickly allows a user to estimate the amount of whitespace in a given region.

For example, after collecting the requisite data, we produced estimates of the amount of whitespace in Canada in under an hour. To demonstrate the power of our software, we present novel results on whitespace availability in Canada and Australia. However, the true potential of WEST lies in the ability to configure it to use existing or hypothetical rulesets. We thus use WEST to compare the FCC and Industry Canada (IC) rulesets, showing that each citizen loses approximately one whitespace channel, mainly due to the increased size of IC’s separation distances as compared to the FCC’s. We also showed that although the effect of taboo channel exclusions (a notion introduced in the IC ruleset) is small in Canada, it would be much larger if applied to the USA. The identification of the real-world effects of these regulatory decisions was made possible by WEST’s ability to create “chimera rulesets,” i.e. mosaics of the IC and FCC rules, so that we could examine each variable in isolation.

Finally, we describe the high-level design of WEST. The modular design makes it easy for users to combine, replace, modify, or remove various components to achieve the desired effect. We sincerely hope that the community will use and contribute to WEST, turning it into an even more powerful tool than it is today. If real-world data were at your fingertips and easy to use, what would you do?

## I. INTRODUCTION

Although it may appear from recent spectrum auctions<sup>1</sup> as though all useful spectrum is fully utilized, studies have shown again and again that this is incorrect. For example, [2] and [3]

<sup>1</sup>The 2015 AWS-3 auction sold 65 MHz of spectrum for almost \$45 billion USD [1].

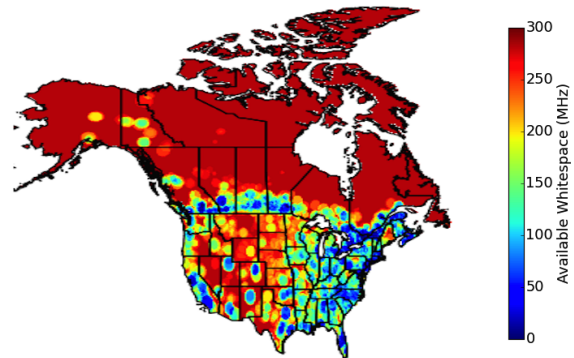


Fig. 1. Map showing the amount of whitespace (in MHz) available to a fixed device in North America under the FCC ruleset.

have shown that a large fraction of allocated spectrum actually lays fallow. Since it is not practical to make sweeping changes to existing allocations and deployments, dynamic spectrum access (DSA) is critical for harnessing this spectrum that is allocated yet unused [4].

The incarnation du jour of DSA is as TV whitespaces, the interstices between over-the-air TV stations. The Federal Communications Commission (FCC) in the USA made use of the whitespaces legal in 2008 [5] (with updates in 2010 [6] and 2012 [7]) and Singapore followed suit in 2014 [8]. Ofcom in the UK [9] and Industry Canada [10] did the same in early 2015. We fully expect that it is simply a matter of time before TV whitespaces around the world are legal to use.

At the same time, other bands are under consideration for spectrum sharing. In the USA, the 3550-3650 MHz and 5350-5470 MHz bands are undergoing sharing investigations [11], [12]. In other countries, GSM whitespaces [13] are already being used (albeit illegally).

One of the most common questions asked when considering opening up a new band or region for whitespace use is: what is the size of the opportunity? That is, “how much whitespace is there?” Early papers [14] on TV whitespace in the USA quantified this in terms of MHz available across the USA, and later [15] in terms of potential data rates (under a given deployment model). These papers helped inspire future papers quantifying the amount of whitespace in Europe [16], [17].

Other papers have recognized the importance of these studies and called for them to be done in other regions [18]. Some regulators have even started using them to highlight the effects of their regulatory decisions [19].

Despite the universally-recognized importance of these studies, there is no easy way for an interested party (regulator, researcher, or industry member) to carry one out themselves without a lot of preliminary work. Existing solutions include static images on websites [20]–[23] and closed-source software tools [24], all of which work exclusively for TV whitespaces and most only for a single region.

Much of our prior work has relied heavily on our own Matlab code base [25]. While it has been open-source for several years and has several users, it is focused on TV whitespaces in the United States. Because it grew organically throughout the course of our research, it was not designed with flexibility in mind. Finally, it was written in Matlab which is not freely available to all who may wish to use it, nor is it easy to integrate with other tools (e.g. Amazon’s AWS).

After years of experience in the field of policy for dynamic spectrum access, it was clear that there was an unfulfilled need for open-source software which was flexible enough to study a wide variety of bands in any region of the world. As a result, we decided to build WEST [26], a framework for evaluating the whitespace opportunity in any region and with any incumbents. WEST is written in Python and features a modular design which makes it easy to combine, replace, modify, or remove various components to achieve the desired effect. WEST has already been used to study spectrum reallocation scenarios related to the FCC’s upcoming incentive auctions [27] and we hope it will be used for many more papers in the future.

The key idea behind WEST is that most meaningful results stem from a single structured collection of data: a whitespace availability map. WEST provides the tools necessary to produce these maps from a wide variety of data sources. Section III elaborates on this idea that whitespace availability maps are the “thin waist” of whitespace explorations and gives examples of derived data.

This paper is organized as follows. First, we further motivate the design of WEST by presenting novel results on the amount of whitespace in Canada and Australia. We also compare the FCC and Industry Canada rulesets and quantify the real-world impact of their differences. We then briefly show results on the amount of *contiguous* whitespace spectrum available in the United States.

After highlighting some of the key capabilities of WEST, we then describe its design and how it can be extended for use with new regions. Finally, we talk about possible future additions to WEST, including integration of terrain data as well as data and logic for new regions, rulesets, and propagation models. In Appendix A we provide detailed descriptions of the components of WEST.

## II. APPLICATIONS OF WEST

Since WEST was designed to study whitespaces with different rulesets and in different regions, we put it to the test. We show the results of the first public study of the whitespace opportunity in Canada and Australia — under both FCC and Industry Canada regulations. We then analyze the differences between the FCC and Industry Canada rulesets, highlighting not only the regulatory differences between the two but also the *impact* of these differences.

### A. Canadian whitespaces under FCC regulations

As a test of WEST’s extensibility, we carried out an exercise to quantify the amount of whitespace available in Canada *under the FCC’s rules*. This required two pieces of external data:

- A geographic boundary file describing Canada’s borders<sup>2</sup>
- A listing of the Canadian TV stations<sup>3</sup>

The main difficulty lay in finding the data.

Geographic boundary files are not always accurate or without syntax errors. However, once a suitable boundary shapefile<sup>4</sup> was found, it took only 5 lines of code to import the data into WEST. This is in large part because WEST includes support for reading shapefiles since they are a very common geospatial data format.

Industry Canada freely provides their TV station database to interested parties<sup>5</sup> but it is in an ancient format that only Windows computers can read. Google’s spectrum database data download page<sup>6</sup> includes data for Canadian TV stations, but only those near the USA border. However, the FCC has released the full Canadian TV station set<sup>7</sup> as part of the upcoming incentive auction dataset. Once the correct data was found, existing code for USA TV stations was readily adaptable to the Canadian TV dataset.

It took about 2 hours and 200 lines of code to find and import the data described above. It only took 7 lines of code to calculate the number of available whitespace channels and another 7 lines to plot them, as seen in the Canadian part of Figure 1. The source file for this calculation can be found at [https://github.com/kate-harrison/west/blob/master/examples/canada\\_tvws.py](https://github.com/kate-harrison/west/blob/master/examples/canada_tvws.py).

To our knowledge, this is the first study that has been conducted on nationwide whitespace availability in Canada. Although Spectrum Bridge offers a whitespace finder<sup>8</sup>, it is limited to providing a list of available channels at a user-specified location, making nationwide trends impossible to discern.

<sup>2</sup>See <http://www.nws.noaa.gov/geodata/catalog/national/data/province.zip>.

<sup>3</sup>See [http://data.fcc.gov/download/incentive-auctions/Constraint\\_Files/Canadian\\_Allotment\\_List\\_2014May20.xlsx](http://data.fcc.gov/download/incentive-auctions/Constraint_Files/Canadian_Allotment_List_2014May20.xlsx).

<sup>4</sup>A shapefile is a common geospatial data format for Geographic Information System (GIS) software.

<sup>5</sup>See [http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/h\\_sf09484.html](http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/h_sf09484.html).

<sup>6</sup>See <https://www.google.com/get/spectrumdatabase/data/>.

<sup>7</sup>See [http://data.fcc.gov/download/incentive-auctions/Constraint\\_Files/](http://data.fcc.gov/download/incentive-auctions/Constraint_Files/).

<sup>8</sup>See <http://whitespaces-canada.spectrumbridge.com/>.

## B. Australian whitespaces under FCC regulations

Because it was so quick and easy to do, we gathered data for Australia<sup>9</sup> and computed the amount of available whitespace across Australia, despite the fact that there are no candidate whitespace rules for this region. The results are shown in Figure 2.

As expected, a great portion of Australia’s area has copious amounts of whitespace due to a lack of inhabitants. The populous coastal regions, however, are doing somewhat better than expected: after the digital transition, about five channels allocated for TV use were not actually used. Also, a quick look at the locations of TV stations in Australia (on Google Earth) tells us that the stations are much more spread out along the coastal regions than in the United States or Canada. This combined effect leaves Australians with a *minimum* of 140 MHz of whitespace spectrum everywhere. This is confirmed by the CCDF in Figure 4(a). Unlike the United States and Canada, Australia has a wealth of whitespace spectrum waiting to be unleashed by regulators.

Although this work was suggested in 2011 by [18], it has been sufficiently difficult to complete that no one has done it — until now. Once the Australian TV allocation data was in hand, it took about an hour to integrate it into WEST and produce the map below. Some of the adaptations that were unique to Australia were its 7 MHz channel bandwidth and its slightly different frequency allocations<sup>10</sup>, but WEST was able to handle both of these easily.

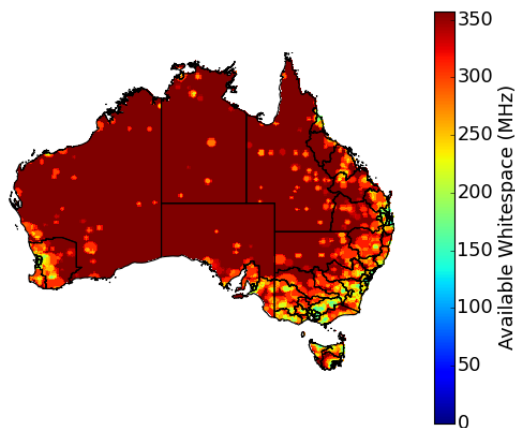


Fig. 2. Map showing the amount of whitespace (in MHz) available to a fixed device in Australia under the FCC ruleset.

<sup>9</sup><http://www.acma.gov.au/Industry/Spectrum/Radiocomms-licensing/Apparatus-licences/list-of-licensed-broadcasting-transmitters> and <http://www.statsilk.com/maps/download-free-shapefile-maps#download-country-shapefile-maps>

<sup>10</sup>The TV bands in Australia are not precisely aligned with those in North America. For example, Australia’s “VHF Band III” covers 137-230 MHz while the F-curves propagation model is defined for only a subset of these frequencies. We were able to produce reasonable estimates for Australian whitespace availability by approximating the service areas of TV stations operating on these out-of-range frequencies.

## C. Studying the Industry Canada whitespace regulations

Industry Canada (IC) released their regulations earlier this year, providing an excellent opportunity to test the flexibility of WEST’s regulatory module<sup>11</sup>. Although the IC ruleset is very similar to that of the FCC, there are a few key differences:

- 1) Definition of protected contour. The target field strength for UHF stations is fixed in the FCC regulations whereas it changes with frequency in the IC regulations (achieving equality with the FCC at 615 MHz, the middle of the UHF band).<sup>12</sup>
- 2) Minimum separation distances<sup>13</sup> are typically larger under the IC regulations.
- 3) The IC regulations also impose minimum far-side separation distances<sup>14</sup>.
- 4) Taboo channels. The IC regulations define “taboo channels” to protect analog stations. This has the effect of banning whitespace devices from not only transmission on the same and adjacent channels, but also on several other channels within the service contour of the analog TV station.

Both rulesets utilize the same propagation curves [28] for calculating the service areas of TV stations and define identical device classes. This overview covers the most important differences between the two rulesets; readers interested in the full set of differences are referred to the source material [7], [29].

Figures 1 and 3 show the amount of available whitespace in North America under the FCC and Industry Canada rulesets for fixed devices. We restrict our discussion to the United States and Canada to keep it brief; there is no reason the same analysis could not be done for Australia. The differences are difficult to discern from these plots alone but are more obvious in Figure 4, which combines census data with information about whitespace availability to show the amount of whitespace available *by population*.

We make two key observations:

- **People have more whitespace in the USA than in Canada.** Regardless of the ruleset used, Americans appear to have a greater number of whitespaces than Canadians. The median Canadian has access to about 5 fewer whitespace channels (30 MHz) than the median American. Although much of Canada’s *area* experiences

<sup>11</sup>Ofcom’s rules are unfortunately unsuitable for use outside the UK because they require proprietary information that only exists for the UK and is only available to specific entities. Singapore’s rules are similarly very purpose-built and hard to generalize outside of Singapore.

<sup>12</sup>We assumed uniformly flat terrain while calculating the protected contours, because WEST does not yet support terrain data. Integrating terrain data into WEST is an important line of future work.

<sup>13</sup>A device may only utilize co-channel whitespaces if it is at least this far from the nearest protected TV contour. Different minimum distances are defined for adjacent- and taboo-channel operation. The distances may also depend on the characteristics of the whitespace device and the TV station.

<sup>14</sup>The far-side separation distance defines the minimum separation distance from the *far* side of a TV station’s protected contour (in contrast, all other separation distances are defined with respect to the nearest point on the contour). See Section 4 of <http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10928.html> for additional details.



Fig. 5. Block diagram showing how the chimera rulesets were created from the FCC and IC rulesets.

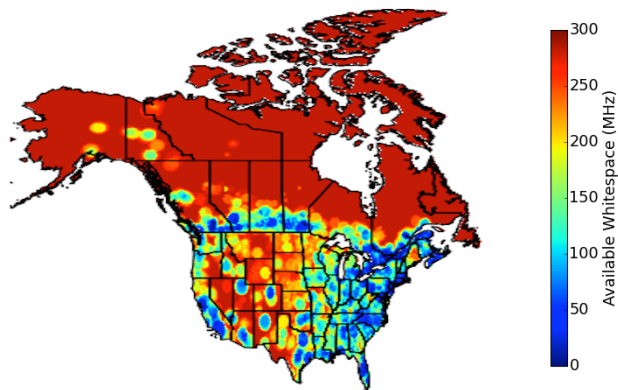


Fig. 3. Map showing the amount of whitespace (in MHz) available to a fixed device in North America under the Industry Canada ruleset.

an overabundance of whitespaces, its population is more concentrated in urban areas which are typically less rich in whitespace.

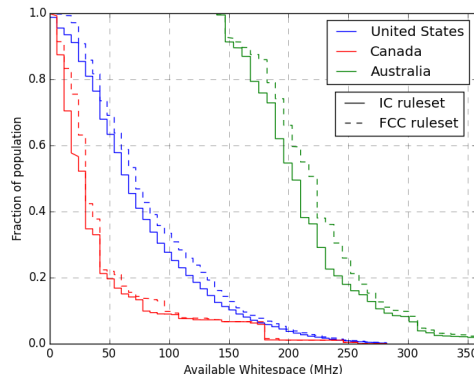
- **The FCC ruleset appears to be more permissive in both the USA and Canada.** In the USA, each person has approximately one additional whitespace channel under the FCC ruleset. The difference is less pronounced but still present in Canada.

Fully understanding the differences between the two rulesets and how they are manifested in the real world takes a bit of work. We made use of WEST’s modular design to create “chimera rulesets” which blend together the two rulesets. For example, one such chimera ruleset may be identical to the FCC ruleset *except* that it uses the separation distances specified by the IC ruleset.

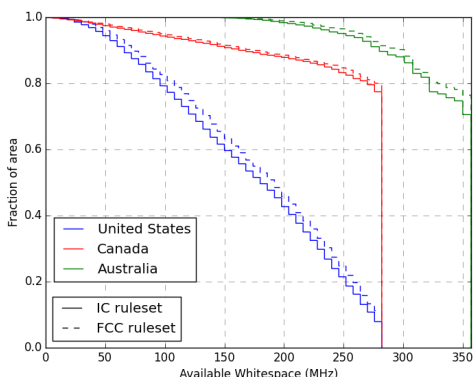
Figure 5 shows how we created these hypothetical chimera rulesets from the FCC ruleset and IC ruleset. In this way we isolate each effect in turn and are thus able to quantify the effect of each decision.

In Canada it is clear that the main real-world difference between the rulesets shows up in the size of the separation distances and, secondarily, in the definition of a TV’s service area. Other ruleset differences have negligible effect on whitespace availability.

However, we see that the United States is significantly impacted by the effect of taboo channels. These restrictions affect only areas serviced by analog TV stations, which in the USA are both more numerous and more likely to appear in urban areas. From this we learn that a ruleset is not necessarily objectively “good” or “bad”: the context in which it is applied



(a) CCDF by population



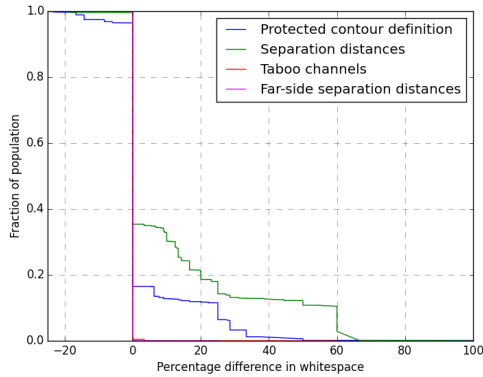
(b) CCDF by area

Fig. 4. Complementary cumulative distribution functions (CCDFs) of available whitespace by population and area in the United States, Canada, and Australia for fixed devices.

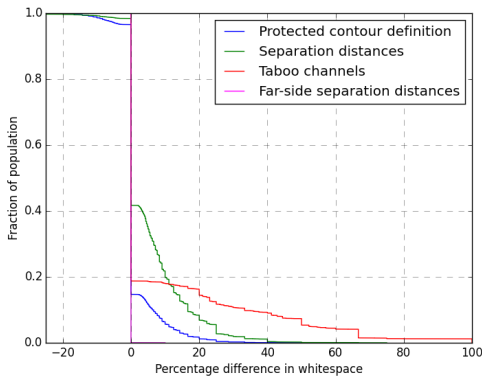
matters a great deal.

We now describe in greater detail how each of the ruleset differences impacts whitespace availability:

- 1) *Separation distances*: For almost all TV stations, the IC ruleset mandates greater separation distances from stations’ protected contours than the FCC ruleset. Under the IC ruleset, separation distances are greater by anywhere from 1 kilometer to 30 kilometers. Consequently, whitespace devices need to maintain a much greater distance from TV stations to be allowed to operate than under the FCC ruleset. This results in a decrease in available whitespace across both Canada and the United States.
- 2) *Target field strength*: The target field strength of a TV station, and therefore its defined service contour, differs by at most a kilometer between the two rulesets. This



(a) Canada



(b) United States

Fig. 6. Complementary cumulative distribution functions (CCDFs) of the percentage change in whitespace by population due to each effect being applied incrementally in the United States and Canada. For example, using the IC-mandated separation distances instead of the FCC-mandated separation distances costs about 20% of Canadians about 20% of their whitespace.

has the small effect of slightly increasing or decreasing the amount of available whitespace for a relatively small number of people in both the United States and Canada.

- 3) *Taboo channels*: The introduction of taboo channel exclusions in the IC ruleset affects whitespace availability only in locations that are served by analog TV stations. In Canada, only 2% of TV stations are analog, and they serve only 2% of the population. In contrast, analog TV stations serve 27% of the USA population. So while taboo channel exclusions have a negligible effect on available whitespace in Canada, they would cause a substantial decrease in available whitespace in the United States.
- 4) *Far side separation distances*: Far side separation distances cause additional loss in whitespace only around stations with very small protected contours. This condition affects the protected contours of only 2-3 stations in both the United States and Canada, which translates to 0.3% of studied locations in Canada and 0.1% of studied locations in the United States. Therefore, the far side separation distance condition would affect whitespace

availability in a negligible way.

The power of WEST is clear from this exercise. First, it allows the quick exploration of whitespace availability in another region as discussed in Section II-A. Second, it allowed us to easily create “chimera rulesets” in order to explore the real-world effect of regulatory decisions. Note that any ruleset can be modified arbitrarily and need not be based on a real-world ruleset. For example, we could just as easily quantify the effect of adjacent-channel exclusions by modifying our implementation of the FCC ruleset to remove these exclusions. Other publicly-available tools simply do not support these kinds of operations and explorations.

#### D. Contiguous whitespace channels

One of the major barriers to whitespace utilization is the fact that whitespaces represent discontinuous spectrum. Since whitespaces are only found in the interstices of the TV spectrum, there is no guarantee that whitespace channels will be adjacent in frequency. This presents challenges in the design of whitespace devices.

With WEST, it is simple to calculate the number of contiguous whitespace channels: it can be done in less than 50 lines of code<sup>15</sup>. Figures 7 and 8 show the result. We see that most places (Dallas, TX, and New York City being the most notable exceptions) have at least two contiguous whitespace channels available. We also see that the median United States citizen has about 5 contiguous whitespace channels, translating to 30 MHz of contiguous whitespace spectrum. The results are similar for portable devices with the notable exception that their maximum number of contiguous channels is limited by the number of whitespace channels which are open for use by personal/portable devices<sup>16</sup>. This high availability suggests that systems should be designed to take advantage of contiguous spectrum when it’s available, with the ability to fall back to a single whitespace channel if necessary.

### III. USING WEST

Creating whitespace availability maps—like those shown throughout this paper—is remarkably easy with WEST. In fact, these maps are merely the most basic output: as Figure 9 shows, there are many ways of exploring and presenting the data.

The user begins by specifying the device (e.g. fixed vs. personal/portable) and Region (e.g. United States) of interest. The Region object contains information about the protected entities in that region, as described in Appendix A. Since WEST’s calculations are done on “pixelized” maps, the user must also specify the resolution for the output data in the form of a DataMap2D, which is essentially a 2-D matrix with geographic metadata.

This data is used as input to a Ruleset object (e.g. one implementing the FCC 2012 ruleset) along with a channel

<sup>15</sup>See [https://github.com/kate-harrison/west/blob/master/examples/contiguous\\_channel\\_count.py](https://github.com/kate-harrison/west/blob/master/examples/contiguous_channel_count.py).

<sup>16</sup>Currently portable devices are only allowed to use TV channels 21-51 while fixed devices have access to up to 17 additional channels.



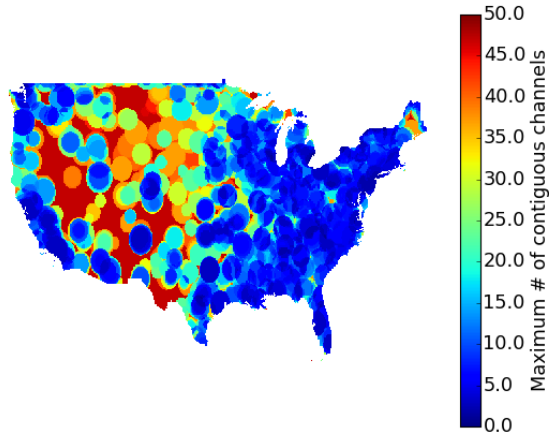


Fig. 7. Map showing the maximum number of contiguous whitespace channels available to a fixed device in the United States.

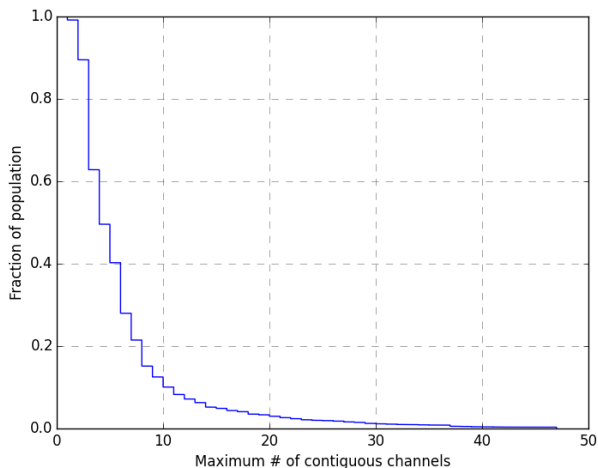


Fig. 8. Complementary cumulative distribution function (CCDF) of number of contiguous whitespace channels available by population in the United States for fixed devices.

number. The Ruleset object then calculates which locations are considered whitespace on that channel and returns a binary DataMap2D holding this information.

From here, the possibilities are numerous:

- One of the most common things — as shown in Figures 1 and 2 — is to perform this operation for all whitespace-enabled channels in the region and create a map of the **whitespace channel count**.
- By repeating this process for a second ruleset and then subtracting the results, one can also create a **whitespace delta map** which highlights the differences between two rulesets. This can also be done to compare e.g. fixed vs. portable whitespace availability.
- Seeing a **CCDF by area or population** of the same data can often lead to additional insights and is a natural way

to quantify the effect, as seen in Figures 4 and 6.

- Other papers of ours [27] utilized the same machinery to compare band reallocation with the whitespace approach for recovering spectrum via **plots of the Pareto curves**.
- The same paper also used **2D histograms** to compare whitespaces under two different scenarios. Details on how WEST was used to generate these figures can be found in [30].
- With the additional assumption of a self-interference or deployment model, one could also calculate **data rate maps** like those in [15].

The key is that all of these results come from further processing of a basic data type — the whitespace availability map — which is what WEST is designed to compute.

#### IV. EXTENDING TO OTHER REGIONS

Extending WEST to support a new region, as was done in Section II, is quite easy once the correct source data is in hand. Using Canada as an example, we took the following steps:

- 1) Create a new BoundaryCanada class. This class represents the geographic boundary of the region and is primarily used for display purposes (e.g. drawing provincial borders). Since there is built-in support for shapefiles in the Boundary class, the new class only needed to specify the filename for the source data once an appropriate shapefile was found.
- 2) Create a ProtectedEntities class to read in and hold data about USA and Canadian TV transmitters. Although the code is specific to the format of the source data file, much of the code from the USA-only data files could be reused.
- 3) Create a RegionCanada class to specify e.g. which channels are available as potential whitespace and which entities should be protected (i.e. the class from Step 2).
- 4) (Optional) Create a DataMap2DCanada class which will, by default, have latitude and longitude bounds appropriate for Canada. This class specifies how the region’s area will be pixelized. Creating a specific DataMap2D subclass makes it both easier to reference as well as ensures compatibility between generated data.

These classes are described in detail in Appendix A. The code for all of these steps can be found at [https://github.com/kate-harrison/west/blob/master/examples/canada\\_tvws.py](https://github.com/kate-harrison/west/blob/master/examples/canada_tvws.py). It uses USA and Canadian TV station data with the FCC ruleset to compute a map estimating the whitespace availability in Canada.

#### V. EXTENDING TO OTHER RULESETS

The analyses we carried out in Section II were made possible primarily because the architecture of WEST enables us to easily create extended or modified rulesets, whether based on real, candidate, or hypothetical rulesets.

The first ruleset we created to compare to the FCC ruleset was a reasonably faithful implementation of Industry Canada’s 2015 ruleset. Implementing the Industry Canada ruleset required creating a new subclass of the Ruleset class (see

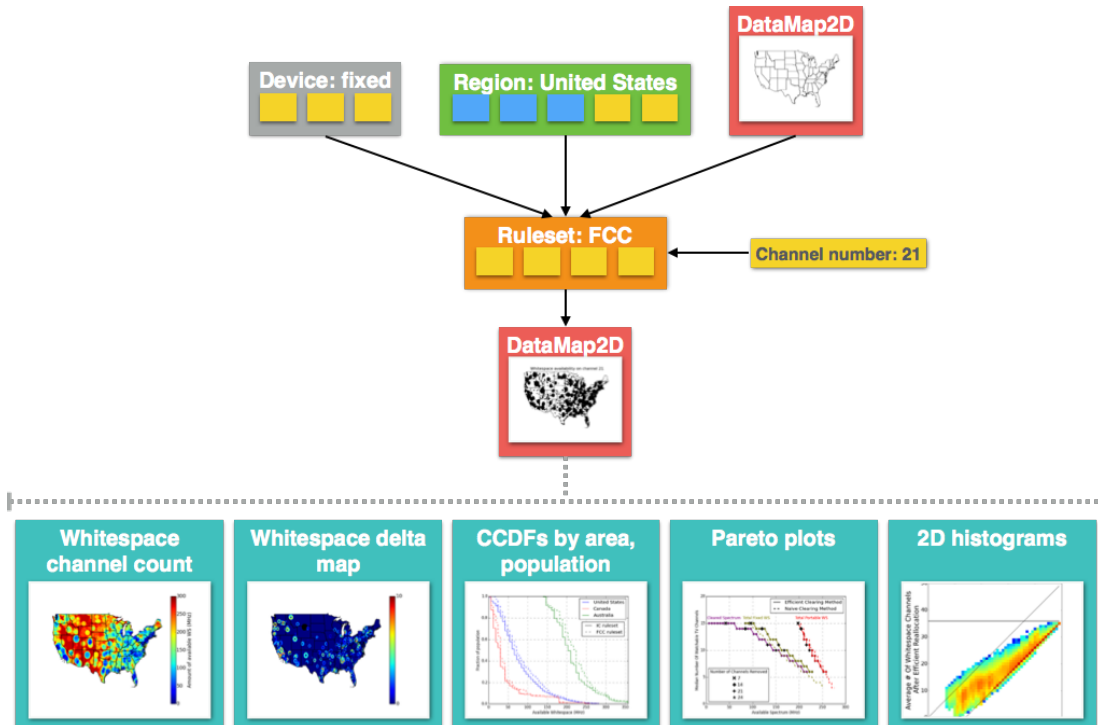


Fig. 9. Flow diagram for generating a whitespace availability map and derived output.

Appendix A for more details about this class). Since there are many similarities with the FCC ruleset, much of the code could be borrowed. By obeying the interface defined by the Ruleset class, we ensured that the FCC and IC rulesets could be used interchangeably.

We next created “chimera rulesets” as described in Section II. Due to the carefully-planned structure of the code, we were able to easily add or remove ruleset components with only a few lines of code. Exploiting the structure of the Ruleset class enabled us to create all three chimera rulesets in less than 20 *total* lines of code.

What makes WEST so powerful is its ability to support not just implementations of existing rulesets, but also the creation of hypothetical rulesets. The advantage of these hypothetical rulesets is twofold. First, regulators can test, ahead of time, the empirical effects of their candidate rulesets on available whitespace, enabling them to come up with better designs. Hypothetical rulesets are also useful to researchers, as they can facilitate more detailed whitespace analyses across different regions. Second, we can quantify the whitespace availability in countries that have not yet enabled the use of whitespace spectrum by applying other countries’ existing rulesets. This is exactly what we did in Australia since the Australian Communications and Media Authority (ACMA) has not developed a candidate ruleset yet; this allowed us to generate the first public maps estimating whitespace availability in the region.

## VI. CONCLUSIONS

This paper began by presenting novel results on the amount and location of whitespaces in both Canada and Australia. It

continued with a comparison between the FCC and Industry Canada whitespace rulesets as applied to the United States and Canada. We showed that the FCC ruleset is more permissive than the IC ruleset, particularly in the USA. Via explorations with WEST, we discovered that this was primarily due to the effect of increased separation distances from stations’ protected contours, and taboo channel exclusions.

The results above are only made possible by WEST, an open-source software package we developed to help researchers, industry members, and regulators alike. Our goal with WEST is to enable data-driven analysis of both the current and the hypothetical whitespace opportunities. It is designed to be flexible enough to work with a variety of regions, protected entities, rulesets, and propagation models. This paper has demonstrated some of the power of WEST but has not exhausted its capabilities. We look forward to future papers in the community that will use WEST in new and interesting ways.

We strongly believe that regulations in particular should be data-driven, giving regulators full understanding of the tradeoffs they are making between interested parties. This not only increases transparency but also the ability of regulators to strike the tradeoff points they desire. Furthermore, it gives them the tools they need to independently analyze these tradeoffs rather than relying on industry members and lobbyists for these results.

## VII. FUTURE WORK

Since WEST is open-source, we expect members of the spectrum sharing community to contribute their own data-

driven perspective on whitespaces in the natural course of their research. We strongly encourage interested parties to build on WEST and share their extensions with the community if and when possible. In particular, we hope to be able to add the following to WEST:

- Terrain data (we currently assume the world is flat which yields circular contours)
- More regions (currently only USA, Canada, and Australia are supported)
- More protected entities (currently focused on TV; also includes radioastronomy and PLMRS/CMRS; could add MVPD, BAS links, etc.)
- More rulesets (e.g. DSA model rules [31], any European rules that may come out)
- More propagation models (e.g. Hata)
- Application to another band (a good test of flexibility will be application to e.g. the 3.6 GHz band)

As with most open-source projects, WEST relies on the community for growth. Anyone wishing to contribute to WEST is encouraged to send an email to the authors.

But the goal is not just to add support for existing concepts like those listed above: we also want to see WEST used in new and creative ways and by a variety of users. The community as a whole will benefit greatly from seeing perspectives more diverse than those of a single research group. To that end, we encourage the reader to pursue data-driven explorations – whether they use WEST or not.

An increasingly relevant aspect of whitespaces is their variation over time. While TV broadcasts are relatively static in nature, we expect that incumbents in other bands will have behavior that is more dynamic. For example, ship- and airborne radar operating in the UNII-2B (5.35-5.47 GHz) band would cause fluctuations in the amount of available whitespace. These incumbents may have less predictable behavior than others, e.g. satellites with a known trajectory (also operating in this band). How to quantify time-varying whitespaces in a meaningful way is an open question.

One candidate solution is to derive a probability mass function (PMF) of available whitespace at each location. This is difficult to digest in its raw form, so taking “slices” of the PMF (e.g. “how much whitespace will be available at least 95% of the time?”) may help with interpretation of the data. We expect that this would be useful for business planning when establishing systems that have smaller spatial footprints than the incumbents. Planning for larger networks might necessitate stronger requirements, such as having a minimum amount of whitespace available within the entire footprint of the network (and perhaps even the *same* whitespace).

## APPENDIX A MODULES

In this appendix, we describe the design of WEST. WEST contains the following high-level modules:

- **DataMap** (DataMap2D or DataMap3D): the standard format for data is a 2-D matrix with geographical

metadata. A plotted DataMap2D yields figures like Figure 2. A DataMap3D allows for logical aggregation of DataMap2D objects.

- **Population**: reads in population data and creates a population DataMap2D.
- **Region**: specifies various parameters about a region such as which channels are available for whitespace use, channel bandwidth, and the set of protected entities.
- **Boundary**: specifies the boundary of the given region; mostly used for plotting purposes.
- **ProtectedEntity**: specifies an entity (e.g. TV station) that may be eligible for protection.
- **ProtectedEntities**: a collection of ProtectedEntity objects (e.g. the set of all TV stations in the United States).
- **Ruleset**: describes how to protect various entities.
- **Specification**: describes an experiment in a parametrized way; used to quickly recall or generate data.

Each of these will be discussed in turn in the following subsections.

### A. ProtectedEntity

A ProtectedEntity object describes an entity which may be eligible for protection from whitespace devices. Figure 10 shows an example of a specific protected entity: a TV station. The object contains the essential information about the protected entity (e.g. location, height, transmission power, frequency, transmitter type) but notably does not contain any information about the nature of the protection. The nature of the protection is inherently a property of the Ruleset, not the protected entity itself.

Other protected entities may include radioastronomy sites or PLMRS sites, as in the case of the TV whitespaces in the United States.

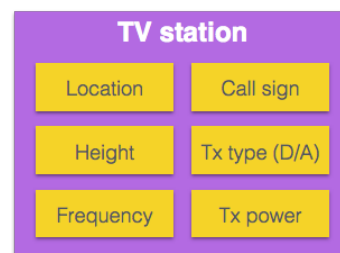


Fig. 10. Visual representation of a ProtectedEntityTvStation object.

### B. ProtectedEntities

A ProtectedEntities object is a collection of ProtectedEntity objects of a single type. For example, Figure 11 shows a collection of TV stations. The ProtectedEntities class is responsible for specifying the data source and parsing it to create individual ProtectedEntity objects.

While some ProtectedEntities objects will differ in the type of ProtectedEntity they contain, others will differ based on the source of the data. For example, a user may create a ProtectedEntitiesTvStationsFromGoogle[DATE] class which ingests a file downloaded from Google’s spectrum database



data download page [32] and another ProtectedEntitiesTvStationsFromTvQuery[DATE] class which ingests data from the FCC’s TV query website [33]. In this way, the user can easily switch between the two datasets by simply specifying the class s/he wishes to use.

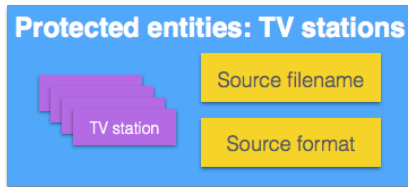


Fig. 11. Visual representation of a ProtectedEntitiesTvStations object.

### C. Region

A Region object contains a collection of ProtectedEntities which may be afforded protection within the region. It also contains geographical information (in the form of a Boundary object) which describes the physical boundary of the region.

Finally, it contains information on the channels (and their corresponding frequency representation) which *may* be available for whitespace use, subject to the protection of the protected entities. A distinction is made between channels which may be available for portable devices vs. fixed devices. While this information could also be contained in the Ruleset class, it fits more naturally in the Region class.

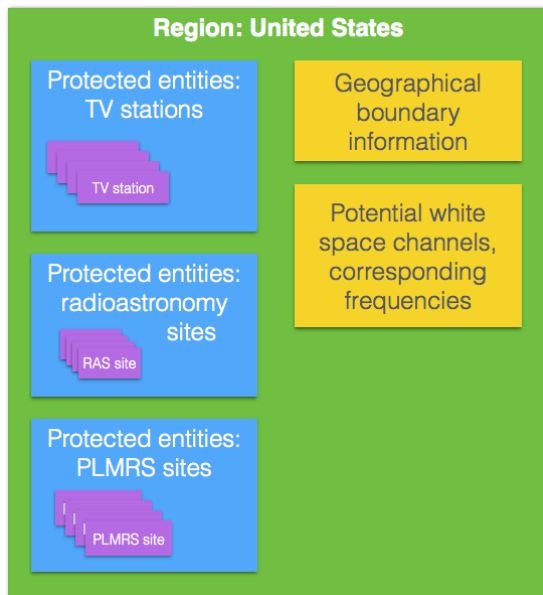


Fig. 12. Visual representation of a Region object

### D. DataMaps

Information is collected in objects called DataMaps. They come in two varieties: 2D and 3D. Typically, a DataMap2D will be used to describe a single piece of geographically-dependent information, e.g. the availability of a single channel for whitespace use. DataMap3D objects, on the other hand,

contain multiple pieces of geographically-dependent information, e.g. the varied availabilities of a collection of channels for whitespace use.

A DataMap2D is essentially a two-dimensional matrix with metadata and helper functions. It is specified by its geographical bounding box and the number of latitude and longitude divisions (i.e. resolution). DataMap2D objects typically but not necessarily describe points within a Region, as suggested by the image in Figure 13. Two DataMap2D objects are considered comparable if they have the same geographic boundary and resolution.

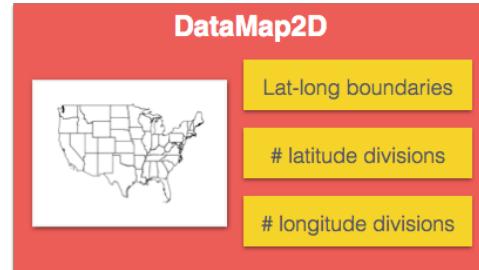


Fig. 13. Visual representation of a DataMap2D object.

A DataMap3D is little more than a collection of DataMap2D objects and associated helper functions to facilitate the combination of the DataMap2D objects (e.g. pointwise summation). Each constituent DataMap2D is called a layer and has a unique label. Layers within a DataMap3D must be comparable and this is strictly enforced.

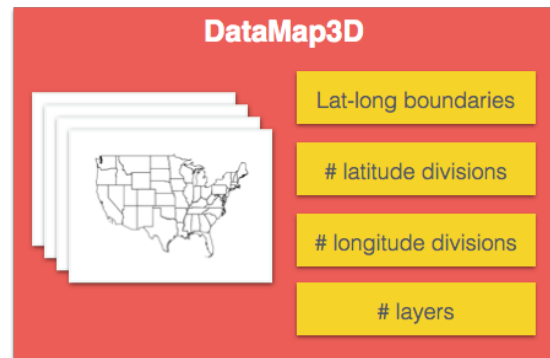


Fig. 14. Visual representation of a DataMap3D object.

### E. Submaps

DataMap2D objects have the ability to extract a submatrix of themselves and its associated metadata, creating another DataMap2D. This allows for more regional processing of data. Submaps are themselves DataMap2D objects and can therefore be used in the same way as the parent DataMap2D.

A submap is created by specifying its geographic bounding box to the original DataMap2D. Steps 1 and 2 of Figure 15 shows a visual representation of this process. The submap is populated with a *copy* of the data in the original DataMap2D. To use the values from the submap in the original DataMap2D, the submap must be “reintegrated.”

The submap infrastructure was used heavily in [27]. Because we were computing the amount of available whitespace under tens of thousands of different TV station allocation scenarios<sup>17</sup>, it was necessary to cache the protected region of each TV station. A cached protected region was a binary-valued submap of the continental USA DataMap2D. To determine the union of protected regions, we simply reintegrated the submap corresponding to each TV station, combining the parent and submap’s values using logical OR. Figure 15 shows this process for a single TV station.

### F. Ruleset

One of the more complicated objects is the Ruleset object. As shown in Figure 16, it contains the protection criteria for all applicable protected entities and the logic for combining various protection rules. The design of each Ruleset class will depend heavily on the style of the regulations.

WEST currently supports a version of the FCC’s TV whitespace rules in the class RulesetFcc2012. This class was designed to be extensible, with most functions performing a very specific task so that they can easily be replaced. For example, to evaluate the amount of whitespace that would be available using the FCC’s rules but different separation distances, one would simply need to subclass RulesetFcc2012 and overwrite the two functions which return the co- and adjacent-channel separation distance, respectively<sup>18</sup>.

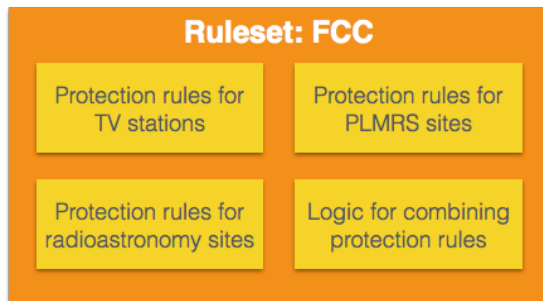


Fig. 16. Visual representation of a Ruleset object.

### G. Specification

Data-driven investigations often cache data in order to trade disk space for computational time. We have found this to be especially necessary when working with whitespace-related data. For example, caching the protected regions as discussed in Section A-E allowed us to perform tens of thousands of computations that otherwise might have taken up to 15 minutes each. In order to facilitate the creation, storage, and retrieval of data, we created the Specification class.

A Specification subclass describes how to create a particular type of data and how to programmatically generate a [hopefully unique] filename for the resulting data. A Specification

<sup>17</sup>While the channel assignment of a given station changed between assignments, its service area was preserved.

<sup>18</sup>These functions are called GET\_TV\_COCHANNEL\_SEPARATION\_DISTANCE\_KM() and GET\_TV\_ADJACENT\_CHANNEL\_SEPARATION\_DISTANCE\_KM().

object is instantiated with the parameters needed to uniquely describe the data. When the user calls the fetch() method, the following happens:

- If a file with the corresponding filename *does not* exist, generate the data and save it to disk. Then return the data to the user.
- If the file does exist, load the data and return it to the user.

In this way the user does not need to worry about whether or not the data already exists when fetching the data. This prevents a lot of boilerplate code and streamlines the entire process.

WEST itself defines several Specification subclasses:

- **SpecificationDataMap** describes a DataMap2D or DataMap3D. It is primarily used as input to other Specifications.
- **SpecificationRegionMap** describes a DataMap2D whose values will be 1 inside the Region’s Boundary and 0 outside.
- **SpecificationWhitespaceMap** describes a DataMap3D whose values will be 1 at locations which are available for whitespace use and 0 otherwise.
- **SpecificationPopulationMap** describes a DataMap2D where the value of each “pixel” is the number of people living inside the area covered by the pixel.

Note that the Specification class *does not* tackle the problem of cache invalidation. If the user edits the procedure for data generation or any prerequisite data, s/he is responsible for recognizing which files are affected and deleting them.

The Specification class also *does not* make any strong guarantees on unique naming. The Specification subclasses defined in WEST itself will generate unique names; however, no such guarantee can be made about user-defined subclasses and hence the user should take care when defining a new Specification.

### H. Other modules

There are several remaining modules which are just as essential yet are more straightforward than the previous modules. We briefly describe them in this section. We also note that WEST fully supports the use of Sphinx<sup>19</sup> which generates HTML documentation for all modules. We refer interested parties to the documentation itself, as that is both more complete and more current than this paper.

1) *Boundary*: This class takes in a geographic boundary of a region (e.g. the outline of the continental United States or the outlines of individual states). Although it is meant to work with generic geographic data, it has built-in support for the common shapefile format. This class is used when creating the logical DataMap2D that describes which pixels are inside a Region, used both to speed up computations as well as to make the map “background” white. It is also used to draw Region outlines when plotting DataMap2D (e.g. the state outlines in

<sup>19</sup>See <http://sphinx-doc.org/>.

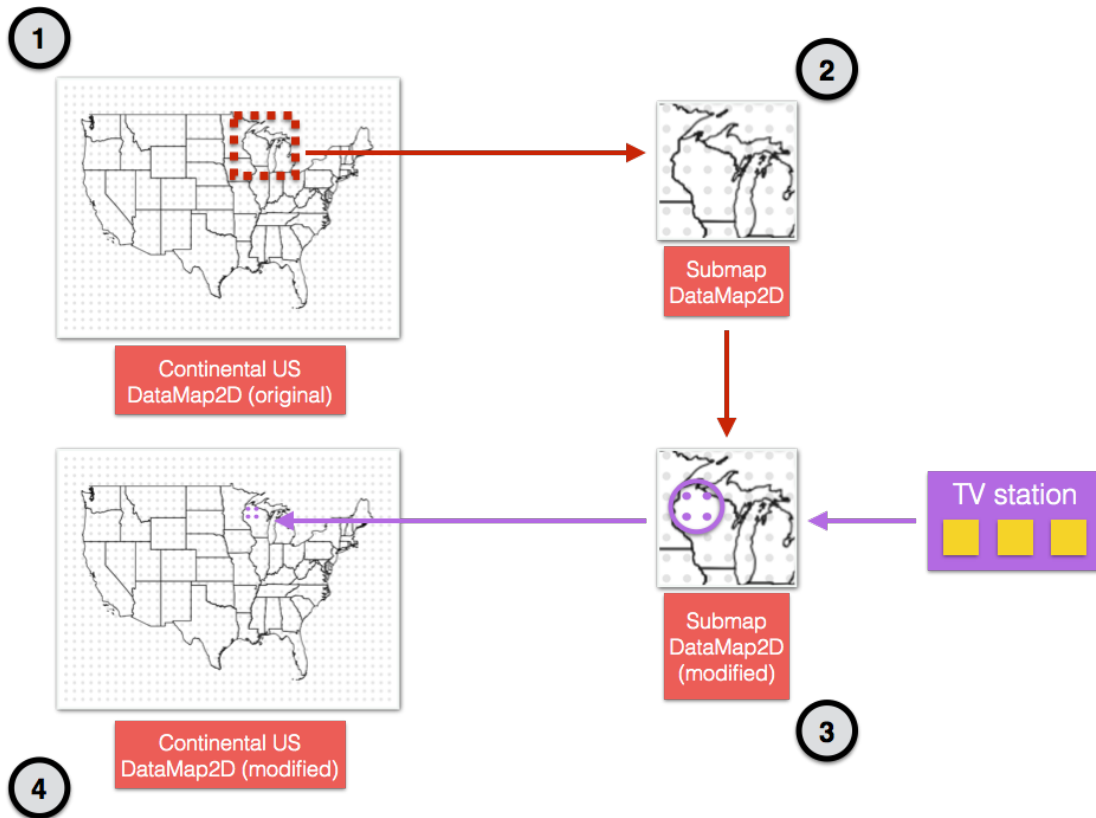


Fig. 15. Submap reintegration process. Step 1 shows the original DataMap2D which contains data for the entire continental USA. Step 2 shows an extracted submap containing data for a portion of the midwest. Step 3 computes which pixels of the submap are not available for whitespace use due to the need to protect a particular TV station. Step 4 reintegrates the submap into the original DataMap2D. Note that the purple pixels in the modified submap are also purple in the modified continental USA DataMap2D.

Figure 1). Note that the Boundary objects used for these two functions may be distinct.

2) *Population*: Figure 4 above used data about each Region’s population to calculate CCDFs *by population*. Our USA population data was obtained from [34], [35], our Canadian population data from [36], [37], and our Australian population data from [38], [39]. The Population class in WEST makes relatively it easy to read in the necessary geographic and census data, automatically linking it together and creating a DataMap2D with pixelized population data. For example, the code to create the USA population map is about 75 lines long.

3) *Plotting*: Plotting functionality is naturally included within WEST. The most notable features include the ability to overlay arbitrary Boundary outlines (of any color) and the ability to use a white background for the image.

4) *PropagationModel*: While WEST currently implements only the FCC’s F-curves, it is possible to add support for arbitrary propagation models. The interface to a PropagationModel object is well-defined and thus PropagationModel objects can be used interchangeably. For example, one could easily specify a new FCC-inspired ruleset which uses a different propagation model to calculate the TV service contours.

5) *Data manipulation*: Since CCDFs form a core part of our explorations, we provide functions which will calculate

the CDF from a given DataMap2D using arbitrary weights. We commonly use the population data as weights to produce CCDFs by population.

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