

Python ARM Radar Toolkit (Py-ART) Roadmap

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1 Introduction and Aims

Radar software is key for producing scientific insight from radar data. There are several platforms for interacting with radar data; the open source variants are well documented in (Heistermann et al 2014). The Python ARM Radar Toolkit (Py-ART, Helmus and Collis, 2016) is one of these. **This document is a guiding roadmap for development for Py-ART.** It sets priorities for ARM funded work and it advises the community which contributions are desired and will receive the most assistance from ARM funded software engineers.

1.1 The Python ARM Radar Toolkit

Py-ART grew out of a collection of radar algorithms generated to support the new radar capability in the ARM program (Mather and Voyles, 2012). The two original features were a Linear Programming (LP) technique for polarimetric phase processing (Giangrande et al, 2013) and mapping radar data onto a cartesian grid.

Shortly after, development on Py-ART began in earnest. ARM provided support specifically to release Py-ART open source. In September of 2012, Py-ART was uploaded to the social coding platform GitHub at <https://github.com/ARM-DOE/pyart>. Py-ART was unofficially bumped to version 1.0.0-Dev in May of 2013 and publicly released. The first "stable" release was 1.2.0 in February of 2015 and the most recent release was 1.7.0 in September of 2016. Release notes can be found here: <https://github.com/ARM-DOE/pyart/releases>.

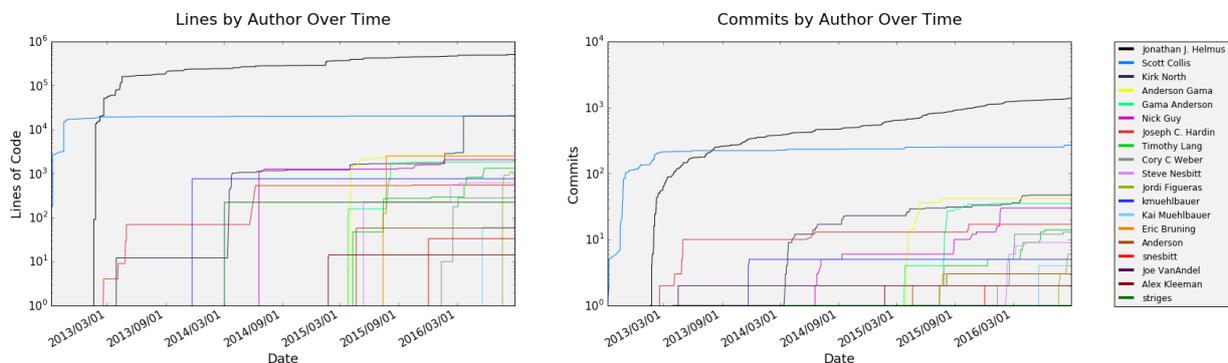


Figure 1: Lines of code by Contributor as a function of time. Note, some lines are automatically generated by Cython to C compilation.

Figure 1 shows the growth of the project as a function of time broken down by contributor. Note that some of the code is C which has been generated by Cython which inflates the number slightly.

Py-ART has benefited from code from 22 individual contributors. This has been enabled by careful implementation of unit tests and continuous integration. Every time a pull request is submitted against the Py-ART codebase a set of tests run and a report is generated so the developers know if a contribution causes any unit tests to fail.

1.2 Value of Py-ART to ARM

Making Py-ART open source and accepting community contributions requires financial support for funding developers to review code and implement automated systems like continuous integration and document generation. Py-ART receives vital support for accepting pull requests, bug fixing, documentation, outreach and education through the ARM program which is part of the Climate and Environmental Sciences Division of the Office of Science in the Department of Energy.

The demonstratable value of Py-ART to ARM is that any code that is contributed to Py-ART can be easily be used by ARM in engineering and operations. Since Py-ART carefully conserves radar metadata including data pertinent to ARM new code can be inserted into Value Added Product (VAP) implementations preserving data pertinent to discovery and dissemination.

Py-ART is used in all VAPs applied to the Precipitation Scanning Radars and could easily be applied to all ARM radars. Currently the Corrected Moments in Antenna Coordinates (CMAC) VAP uses Py-ART including several hundred lines of code that was contributed by non-DoE funded research. Having Py-ART in the community allows ARM to seamlessly incorporate new research from DoE and non-DoE sources into VAPs without the laborious task of transcribing from papers or other languages. In addition Py-ART gives PIs of DoE funded programs and activities a convenient way of answering question pertaining to the openness of their science and their contributions to ARM and DoE.

1.3 Need for a Roadmap for Py-ART

As the collection of algorithms and radars grew it became clear that, while well meaning, third party contributions would subsume other ARM funded efforts by the Py-ART development team. Due to this, and to ensure the toolkit has maximal impact, a roadmap to chart development priorities for the next five years is needed and is the subject of this document.

In summary, the roadmap will prioritize development over the next five years in five years in the following areas:

1. Improved Quality Control (QC) algorithms that can be used to create workflows for building more user accessible radar data.
2. Full support for the emerging Cartopy mapping engine ensuring sustainability of Py-ARTs geospatial visualization tools.
3. Better Documentation, examples and a set of tutorials and courses to allow easy delivery of learning using Py-ART.
4. An ingest of WRF produced NetCDF thus allowing efficient comparison between model and radar produced fields.
5. Work with a third party application to produce cell tracks. Support this effort with visualizations.

The details of these features is expanded on in sections 4 and 5. The roadmap document is broken down into:

1. This introduction
2. The results of the Py-ART roadmap survey and targeted reviews
3. Proposed governance for accepting pull requests
4. Overarching goals for the next five years
5. Specific features that will be a priority for development
6. Measuring impact and the success of the project

We also include a list of papers that have been accepted or are in process that have made use of Py-ART as a reference at the end of this document.

2 The Py-ART Roadmap Survey and Reviews.

2.1 The Survey

In order to produce a development roadmap, we first needed to get the views of users and stakeholders as to what should be in the toolkit. To this end, we designed the Py-ART Roadmap survey. The survey was hosted on SurveyMonkey and we recieved some much appreciated assistance from the ARM outreach office in editing some questions for clarity. The Survey asked users to self identify as either a Py-ART user or not and then asked if they would identify as:

1. A person who mainly works with observational data.
2. A person who uses a mix of modelling and observational data.
3. A person who mainly works with model data.

Unfortunately, we did not get a statistically significant enough sample to discriminate between these groups, so for this document *all user groups will be combined* effectively giving two groups: those that do and do not use Py-ART.

The survey had 35 respondents which were solicited by the ARM and Py-ART mailing lists, Facebook and Twitter. Of those 11 had never used Py-ART and 24 had.

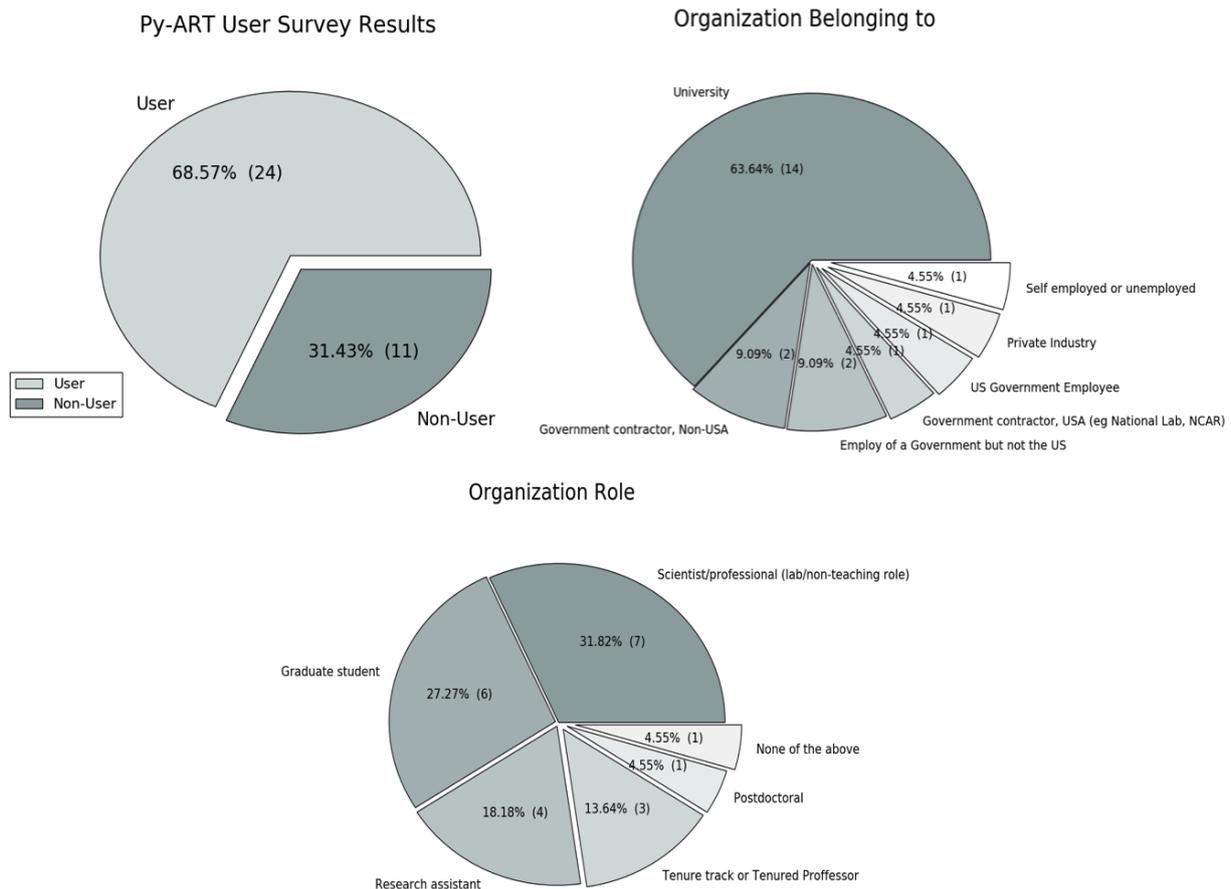


Figure 2: Pie charts showing the split between Py-ART user and non-user respondents and aggregated (user/non-user) self identification of organization and role within that organization.

Respondents were presented with a list of possible additions to Py-ART's suite of algorithms consisting of:

- 1) **Ingest of WRF data to the Py-ART grid model.** The ability to ingest WRF out NetCDF files into the Py-ART Grid data model.
- 2) **Cell/Object Tracking.** The implementation of TITAN's cell tracking (Dixon and Wiener, 1993) or similar to create cell tracks.
- 3) **Multi-Doppler wind retrievals.** Variational or other retrievals of meridional, zonal, and vertical wind velocities from Doppler velocity measurements.
- 4) **More bulk statistics of grid or radar contents (CFAD, echo top heights etc..).** Functions that reduce radar volumes and grids down to descriptive parameters that could be visualized as a time series.
- 5) **Easier "one step" rainfall retrievals.** Making it easier to simply go from a radar volume to a rainfall map.
- 6) **More output formats.** More formats to write to.

7) **More input formats.** More ingests.

8) **Quasi-Vertical Profile reconstruction from a list of radars.** A specific case of item 4 along the lines of (Ryzhkov et al, 2016).

9) **More data quality code (eg clutter rejection, biological masks..).** Code to create gatefilters to remove non-meteorological echoes.

10) **Add the option of Cartopy map backend to the existing basemap in RadarMapDisplay.** The ability to use the UK Metoffice developed Cartopy backend for map based displays. Cartopy is newer than the existing basemap backend but is likely to have a longer shelf life due to basemap not being supported beyond 2020.

11) **Ability to handle Radar Spectra and perform retrievals on.** Extension of the Py-ART data model to handle each gate having a spectra consisting of power as a function of velocity or phase. This will allow for an extension into spectra based retrievals such as clutter removal by interpolating over the "zero peak".

12) **More high level retrievals from the literature (Eg DSD, Particle ID..).** Systematic inclusion of various retrievals dealing with particle size retrieval and rain/snow/hail/ice retrievals.

13) **Velocity Azimuth Display wind retrievals.** Ability to retrieve flow vectors as a function of height. Could include advanced techniques such as DVAD (Lee et al, 2014).

Respondents were only presented with the bolded text, the extra information would have been excessive, but it could be assumed that familiarity may have played some role in voting.

METHODOLOGY OF THE RANKING:

A selector drop-down ranks each feature between one and number of options. A count of the responses are multiplied against their ranked rank and summed. An example score would be 3 responses for rank 1 would be 3 points, 4 responses for rank 3 means 12 points, then added together for 15 points. That sum is divided by the total number of responses to that feature giving the feature a weighted ranked score. Having the highest score means that feature is the most important to the users. The example would yield a rank score of 2.14

2.1.1 Non Py-ART Users

Those who identified as non-users of Py-ART were asked "What feature would make you more likely to use Py-ART." In advertising the survey we made a particular effort to get respondents who do not use Py-ART so we did not suffer from an "echo-chamber" effect. Figure 3 shows the results of this question. The most popular weighted rank for new feature from non-users was "More high level retrievals." The item relating to the mapping back-end Cartopy was the least popular, unsurprisingly, since a fair assumption is many of the non-users are also non-Python users and would not even know what Cartopy is. There is no real sudden decrease anywhere along the rankings.

Non-User Rank of Possible New Features

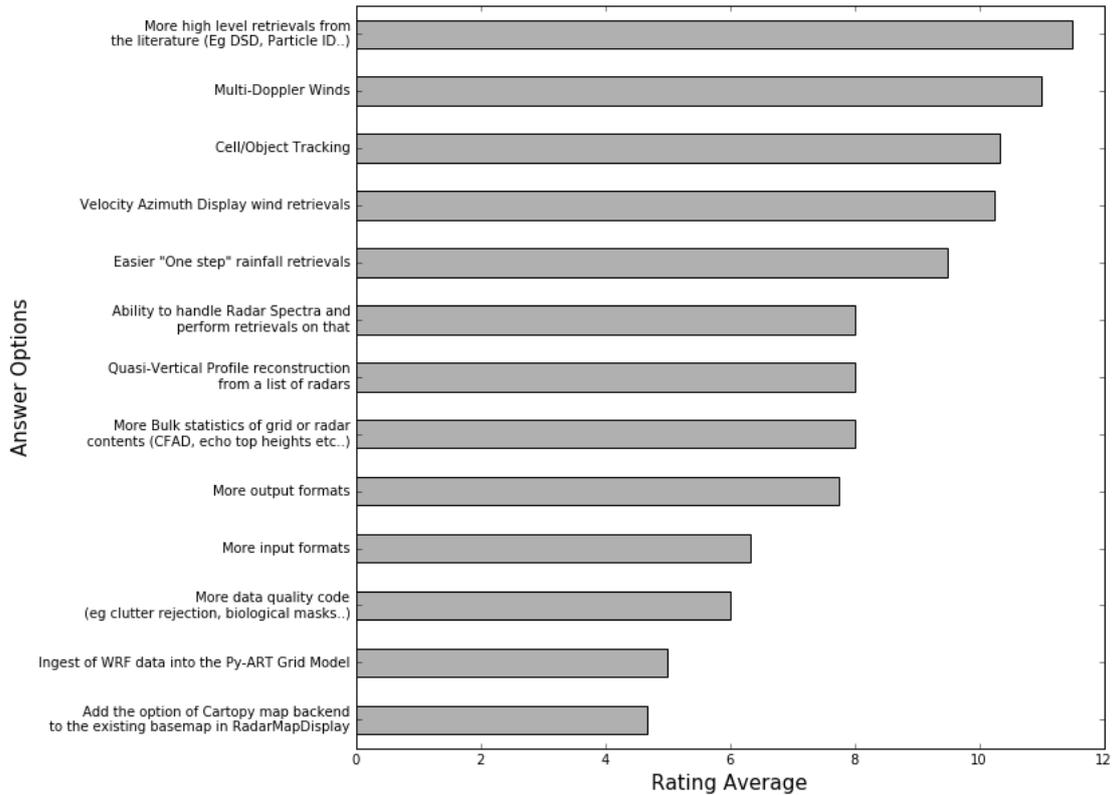


Figure 3: Average ratings for the question "How likely would these added features be to get you to use Py-ART?" aimed at non-users

The survey also asked about barriers that non-users faced to using Py-ART. Figure 4 shows the weighted responses, surprisingly, the number one barrier was "Difficulty to install" followed by "Most of my analysis is done by others in our group." The least popular barrier was "I am not a python user," which is pleasing as it is indicative of a large uptake of Python in the community.

Non-User Barriers to Using Py-ART

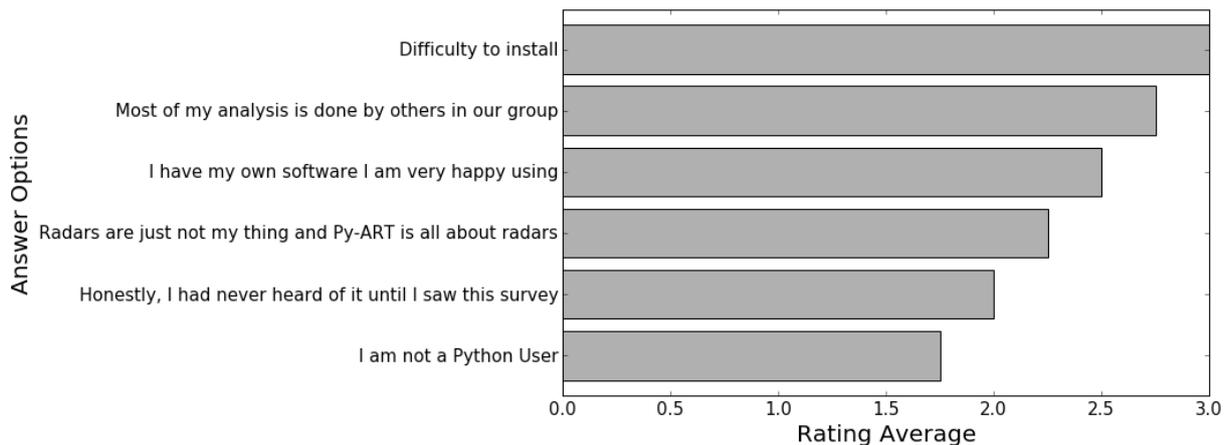


Figure 4: Average ratings for the question "What is preventing you using Py-ART?"

2.1.2 Py-ART Users

With Py-ART users, in addition to asking what feature they desired, the survey also asked them to identify their favourite feature. Figure 5 shows the weighted rankings for the responses. Plotting/visualization was the most popular feature closely followed by an appreciation for the wide variety of formats that Py-ART can read. While unsurprising, this is in-line with the development priorities of Py-ART to-date as the team sees the two biggest barriers to new users of radar data being the reading of exotically formatted files and working out what those files contain. Rankings decreased gradually with a notable break when it came to "Knowing VAPS will work with ADI/ARM systems." Even though this is one of Py-ART's primary aims (to enable PI developed data to integrate easily with ARM systems), this is not surprising. If anything, the development team is a victim of their own success in marketing Py-ART to the wider community. It does show, however, we have some work to do in helping DoE funded PIs in using the toolkit and advocating that funded retrievals be implemented in Py-ART.

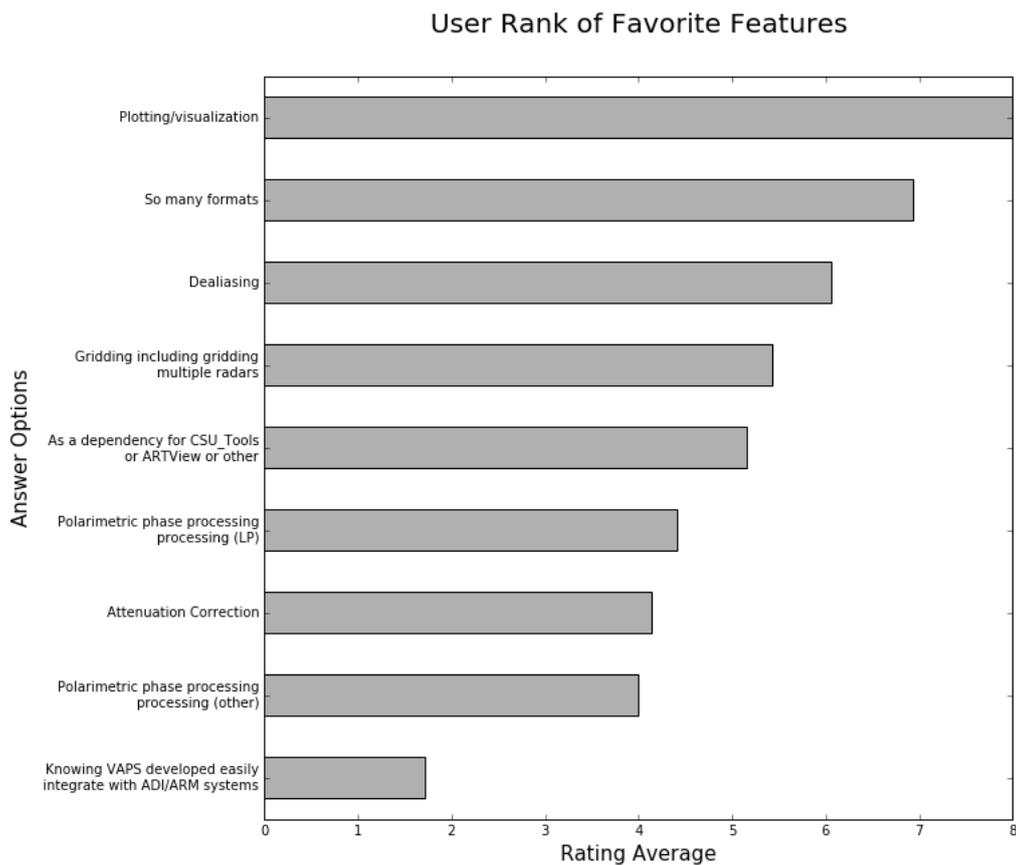


Figure 5: Average rating for the question to users "What is your favourite feature of Py-ART?"

Figure 6 shows the weighted ranks for desired new features for existing Py-ART users. Figure 6 shows several key differences to figure 3. Multi-Doppler retrievals is now the most popular feature, very closely followed by Cell Tracking. And notably, more literature based techniques is the lowest desire by existing users. Perhaps because many of them, using Py-ART's easy to use data model, have implemented many of these techniques at their home institutions.

User Rank of Possible New Features

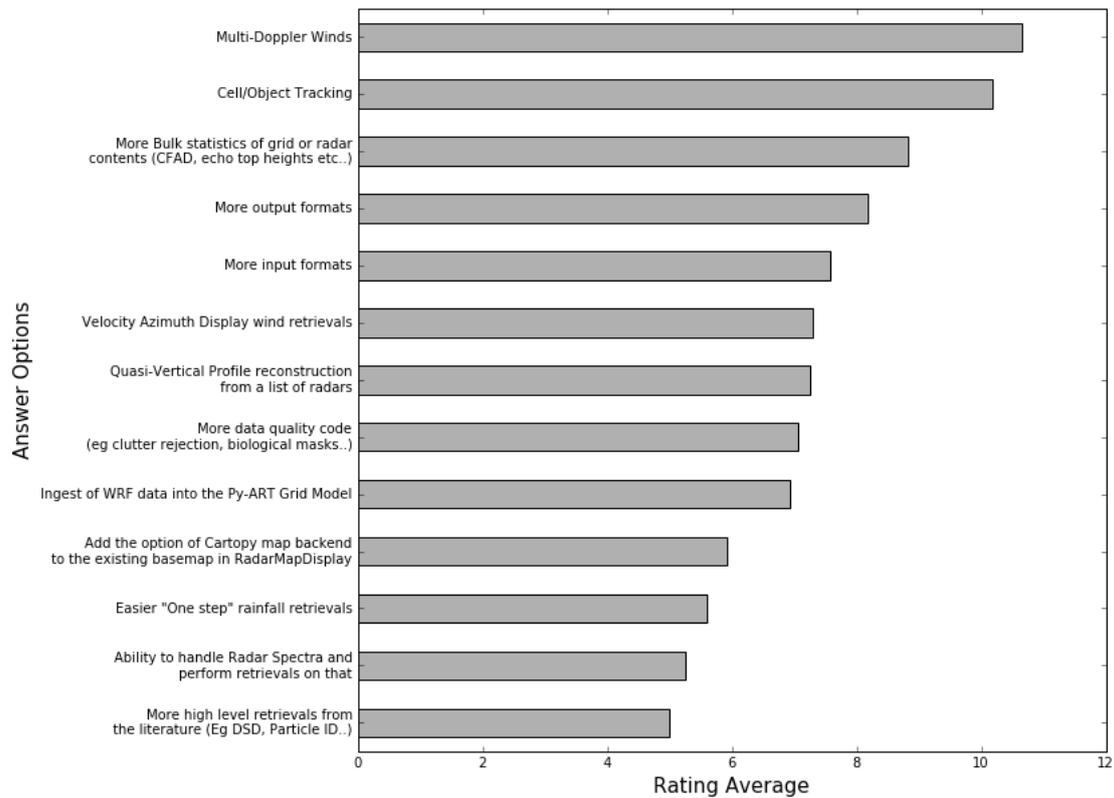


Figure 6: Average rating for the question to users "What features would you like to see added to Py-ART?"

As well as having users pick from feature lists designed by the survey, developers' free-form answers were solicited with the questions "what would be Py-ART's Killer app." Users were allowed to enter three items each so they will not all be documented here and are available in Appendix 1. The key take aways are:

- Multi-Doppler retrievals are in high demand from the community.
- A functionality that allows cross-sections through a radar volume between two points is desired.
- Further desires for better dealiasing.

We took the opportunity to ask users about contributing. There were 18 responses to the question "Have you ever contributed to Py-ART?" Of the 18, 22.2%(4) said Yes via pull request through Github, 5.6%(1) said yes, by intellectual property implemented by someone else, 44.4%(8) said no, but they wanted to and 27%(5) said no and they were not interested in doing so.

Finally, we asked those who have not contributed what the barrier was to contributing.

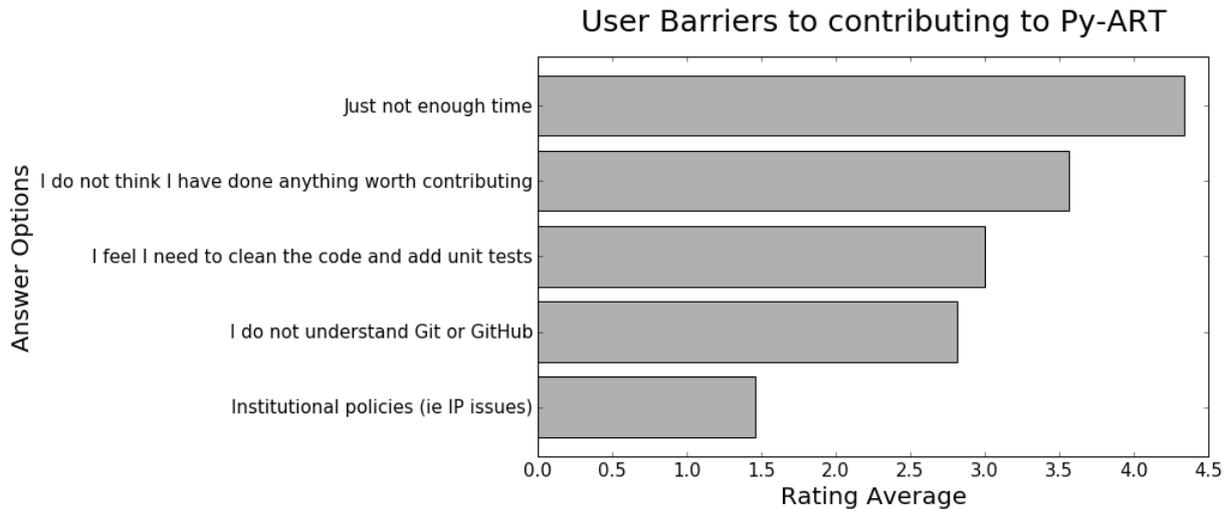


Figure 7: Average ratings for the question "What is preventing you contributing to Py-ART?"

Figure 7 shows the average ranking with the most common barrier being "Just not enough time." This is not surprising, as many researchers would not be judged by open source contributions and would not value such in advancing their careers. The second most common is "I do not think I have done anything worth contributing." This is more than likely a misunderstanding as even things as simple as correcting typographical errors in the documentation is a welcome contribution and small changes are much easier to accept than more substantial changes. The lowest ranking issue is to do with intellectual property issues. This is pleasing, as it means there are few institutional roadblocks to our users contributing.

2.2 Targeted Reviews

Once the general community was polled and the first draft of this roadmap was produced it was circulated to several key science users using two pathways: a review coordinated by the chair of the ASR Radar Science group and a review coordinated by the Py-ART Science lead. The former is a closed review the latter is open although anonymous.

2.2.1 Feedback from the Radar Science Group

There were several key points raised in the collected responses from the Radar Science Group:

- Py-ART is difficult to install for those not familiar with Python.
- There are existing retrieval algorithms for multi-Doppler. Since the methodology is non-trivial those wishing to perform this technique should work with the groups that designed these codes.
- Py-ART should do a better job at engaging the cloud radar community.

In addition we received feedback from the ARM Radar Engineering group on some retrieval code that had been accepted as a pull request which did not accurately implement what existed in the literature. To assuage concerns the group had we have added responsibilities to the Science Lead pertaining to reviewing pull requests for scientific validity in Section 3.

2.2.2 Feedback from ASR funded PIs

The Py-ART science lead contacted four ASR funded PIs *who actively use Py-ART in their institutions*. These reviews were anonymous but the reviewers allowed the reviews to be published openly ¹. The results can be summarized as:

- Py-ART is time saving and a worthwhile activity by ARM.
- The Py-ART roadmap is generally on-point. With a few modifications.
- The ability to ingest WRF and other data into Py-ART's grid data model is desired.

- There should be a focus on basic corrections and QC. For example improving Doppler velocity Dealiasing and Phase Processing.
- Updating Py-ART to work with the new python mapping backend, Cartopy is both needed and a worthwhile effort.
- Multi-Doppler retrievals are desired by the community however Py-ART's strength of making the use of such retrievals so easy could lead to misuse of the technique. Such an endeavour would need to be done carefully.
- Both reviewers one and two believe Py-ART is not the place for simple grid statistics (CFADs) and retrievals (rainfall rate, particle ID). They should either be done by PIs or be in other open source toolkits such as CSU_radartools [4]. Reviewer four did not discuss this point much while reviewer three was in disagreement with reviewers one and two by stating it would be good to have Py-ART as a "one stop shop".

2.2.3 How the roadmap changed as a result of feedback

As a result of feedback from the reviewers the current version of the roadmap differs from the version that went out for review in the following ways:

- Work in QVPs, CFADs, et al ws de-emphasised.
- Work on Multi-Doppler retrievals was significantly de-emphasised.
- A new item was added to the roadmap enabling ingest from WRF files to Py-ART's grid data model.
- The section on QC was expanded and highlighted as as a key priority.
- Note the support of Cartopy as a back end is a priority (2nd behind QC).
- Restrict development on handling radar spectra to the development of a data model.
- Added items regarding outreach, teaching and documentation. Specific focus on developing examples aimed at the cloud radar community.

3 Proposed Governance Structure

The motivation of this roadmap is to ensure that the effort funded by the ARM program is responsive to the needs of the stakeholders of the program. A large task of the lead developer has been in assisting contributors in modifying pull requests (contributions) so that they can be accepted into Py-ART. While it is important to have a consistent standard across the codebase, many of the tasks associated with accepting pull requests can be delegated to others in the community. Currently, there are two ad-hoc defined roles in the Py-ART project: Science Lead and Lead Developer. This roadmap proposes the introduction of a third role: Associate Developer. The roles will be:

Science Lead: Provides high level leadership for the project, organizes outreach and education, and coordinates contributor and stakeholder input to form a long term vision for the project. The Science Lead will also coordinate reviews of the science behind a pull request where some claim has been made. There has been several pull requests accepted in the past which did not accurately implement the methodology from the literature. While it is difficult to catch all inconsistencies the Science Lead will make a judgement on if a pull request requires more review or (in the case of simple fixes) can be accepted as is.

Lead Developer: Responsible for overall architecture of the project. Final arbiter in what pull requests to accept. Develops the required style guidelines and coordinates the associate developers. Coordinates contributions from associated developers to a Contributors Guide (and contributes as well).

Associate Developers: Responsible, as time allows, for doing an initial check of pull requests for suitability and adherence to the Contributors Guide. Contributes to the Contributors Guide.

In seeking Associate Developers, it will be important to seek diversity to ensure there is no single point of failure in providing support to Py-ART. Ideally, the project would have 2-3 Associate Developers. It will be expected that the associate developers will be recognized as key members of the project and are acknowledged accordingly in future publications and presentations.

4 Overarching Goals for Next Five Years

The aim of Py-ART is to lower barriers to doing science with radar data, in particular for Department of Energy stakeholders. From the survey results it is clear that there is a large demand for Multi-Doppler winds. However, on review it was decided that due to the complexities of the retrievals this is better left to a third party. Fortunately during the time of constructing the roadmap a new package, Multi-Dop² was released. Therefore **the addition of multi-Doppler capabilities will not be a priority in the roadmap.**

The addition of Cartopy support polled well and was received well by the reviewers. Fortuitously we recently accepted a pull request that enabled Cartopy use with radial data. Therefore **the addition of Cartopy support for gridded data and the improving of support for radial data will be a priority.** Pull requests adding this capability will receive help from ARM developers. In five years we expect to deprecate Basemap support and have fully functional Cartopy based geospatial visualization capabilities.

In the survey we asked the community about the addition of summary statistics functions like CFADs (Yueter and Houze 1995) and QVPs (Ryzhkov et al, 2016). There was enough demand for it to be included in the first draft of the roadmap. On review it was pointed out by multiple reviewers that these are very easy to implement in Python by the users themselves and Py-ART would better serve the community focusing on other areas. Therefore **pull requests dealing with summary statistics will be treated as low priority. These contributions will only receive limited support from ARM funded developers.**

Cell tracking is an area that also polled well however on review it was decided cell tracking is outside the scope of Py-ART. However there is an activity to make cell tracking available within Python³. Therefore **ARM support for cell tracking as it relates to Py-ART will be limited to accepting pull requests to integrate cell tracking *data* into Py-ART routines.** An example may be a viewer allowing a moving frame of reference.

The addition of a data model for radar spectra received moderate support from polled stakeholders. However it reviewed very well with the Radar Science group as a key way to engage the cloud radar community. Therefore **ARM developers will prioritize helping a pull request submitted adding this capability.** If resources are available ARM support may be made available to develop this ourselves.

The addition of an ingest of WRF data into Py-ART's grid model was not in the stakeholder poll but was mentioned by multiple reviewers. This would be a nice feature add for comparison between radar and model produced data. However it sits right on the boundary of Py-ART's scope. Therefore **pull requests that are nicely documented and require minimal developer time will be accepted.**

Improving and expanding QC capabilities (dealiasing etc..) was not well defined in the poll. However on review of the draft roadmap several users stated better QC routines would *save significant time* in the reaching of scientific conclusions from radar data. Therefore **pull requests improving or adding to Py-ART's suite of QC routines will receive the highest priority by ARM developers.** This includes but is not limited to:

- The Linear Programming based phase retrieval technique (Giangrande et al 2013) which has seen several improvements (Huang et al, 2017) and needs further automation
- The attenuation correction code (Gu et al, 2011) also needs to be improved or replaced.
- Py-ART would benefit from contributions dealing more with basic polarimetric quality control such as (Cao et al, 2016).

Finally, in an oversight, the initial polling did not include a question on documentation, examples and outreach. However this was strongly pointed out on review. Furthermore discussions with maintainers of other major packages yield the same information: *Many users would prefer to see more examples, and use cases of existing features over new features.* Therefore **pull requests with documentation, examples (cookbooks) receive priority support from ARM developers. A specific focus will be on engaging the cloud radar community.** Furthermore the Py-ART development team will continue to engage the community by making training available at DoE and societal (AMS, AGU, ERAD, EGU) meetings. Work will also be undertaken to construct a new repository located on ARM's GitHub page⁴ containing coursework and cookbooks. The Py-ART team will engage with the cloud radar community to better understand their workflows and replicate in Py-ART (with appropriate acknowledgement) as examples.

5 Priority features summary

The Development team will prioritize the acceptance of Pull requests and perform targeted strategic development that adds the features outlined in the following sub-sections. As alluded to in the descriptions from previous sections "Highest priority" means that ARM will accept pull requests that need significant (more than a few days) work or even perform some ARM funded work ourselves. "Moderate priority" means we will accept pull requests that may require some clean up and minor development. "Lower priority" are items where we will only advise the requester on changes required.

5.1 Highest priority

1. **Enhanced quality control features:** Clean up and improvement of existing phase processing and attenuation correction code. New procedures for polarimetric QC. Improved velocity dealiasing and the detection of when this fails.
2. **Improved documentation, examples and training:** Better in-code documentation. Create a new repository with cookbooks that have "shovel ready" examples users can cut and paste. Continue to provide training at meetings and, where appropriate and cost effective, at institutions. A specific focus will be placed on engaging and increasing uptake amongst users of cloud radars.
3. **Cartopy backend:** Extend the cartopy backend to allow display of grid data. Improve radial data display.

5.2 Moderate priority

4. **Support for radar spectra:** A new data model and class `pyart.core.radar_spectra` that allows the storage of spectra as a function of time and range gate.

5.3 Lower priority (would be nice to have)

5. **Support for visualization of cell tracks:** Code that can accept a data frame of lat/lon data of storm cell location and plot these on Py-ART's display systems. An animated viewer that works in a moving frame of reference.
6. **Summary statistics:** Accept well documented, tested (ie very little effort from ARM) code that summarizes radar volumes and gridded data (eg Statistical Coverage Product, May and Lane, 2009).
7. **WRF ingest:** Accept well documented, tested (ie very little effort from ARM) code that ingests WRF produced NetCDF into Py-ART's grid data model.

6 Measuring Impact

As a Department of Energy Supported project it is important but not sufficient to have a roadmap. It is important to monitor impact in order to justify investment and measure the success of the roadmap. The impact of Py-ART can be measured three ways:

- 1) **Growing the number of users and installs:** While it is difficult to get exact statistics, several Py-ART distribution channels provide information of how wide spread the usage of the toolkit is. For example, figure 8 shows that the main repository is viewed by over 100 unique visitors every week and installed 9 times. Success would mean growing this number. Truly metricing this aspect will require periodic surveys. We recommend that surveys are carried out in at the end of the 1st, 3rd, and 5th years of the roadmap.



Figure 8: Number of page views and clones (installs) of the main GitHub repository in a two week period. As the survey showed that the majority of installs are using Anaconda this graph represents a small fraction of the userbase.

2) **Number and success of dependant projects:** Appendix 2 shows projects that require Py-ART as a dependency. In order to be sustainable, Py-ART needs to have a clearly defined scope and the needs of the community outside of this scope are better served with new packages. Therefore, an increasing number and increasing popularity of packages that depend on Py-ART are a measure of success.

3) **Papers and presentations using Py-ART:** Publications are treated by many user facilities as a metric of scientific impact. To date, in just over three years since it was first publicly released, Py-ART has been used in 10 publications. A rate of just over three per year. A metric of success will be to grow this number. Py-ART includes a message on start up encouraging users to acknowledge the ARM program and cite (Helmus and Collis, 2016). We will track and record instances of this appearing in major journals and encourage (via the Py-ART email list, Facebook page, and Twitter feed) users to self report so we can build a Py-ART publications database.

Over the next five years, the success of this roadmap will be judged by more users, a richer ecosystem of applications, and a large body of literature that made use of the Python ARM Radar Toolkit.

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Appendix 1: Free form responses to "Killer App"

These comments have no order to them so they are listed below for reference:

Feature 1 (11 responses):

Easier installation

Dual-Doppler Wind Calculations

More advanced feature with Cross-section cut, based on any two single points, similar to iris

Dual-Doppler Winds

Treat variable like this variable

cross sections between any two points

RadarCollection

Advection correction

More precise data model - e.g in Nexrad Level 3 the width of azimuth gates are not always uniform and in the data format the rays are described with "azimuth of the beginning of the ray" and width of the ray. See relevant ICDs on Level 3.

Multi-Doppler wind retrievals

Additional weighting function options when gridding radar data, besides the Barnes and Cressman schemes

Feature 2: (6 responses)

Dealiasing X-Band Vertical Profiling Radar

More advanced algorithm, like ZDR column detection or NCAR PID algorithms

Easier Geotiff compatibility

Carry along a map image/background to help speed up multiple plotting instances of same radar

Improved dealiasing algorithms

Hydro ID

Feature 3: (3 responses)

Collaboration with SingleDop

Improved dealiasing

Improvements to ARTview to make it replace solo3

Appendix 2: Packages that make use of Py-ART

ARTView <https://github.com/nguy/artview> ARTview is an interactive GUI viewer that is built on top of the Py-ART toolkit. It allows one to easily scroll through a directory of weather radar data files and visualize the data. All file types available in Py-ART can be opened with the ARTview browser.

You can interact with data files through "Plugins". Many functions from the Py-ART package can be selected. In addition, ARTview plugins allow querying data by selecting regions or points visually.

SingleDop <https://github.com/nasa/SingleDop> SingleDop is a software module, written in the Python programming language, that will retrieve two-dimensional low-level winds from either real or simulated Doppler radar data. It mimics the functionality of the algorithm described in the following reference: - Xu et al., 2006: Background error covariance functions for vector wind analyses using Doppler-radar radial-velocity observations. Q. J. R. Meteorol. Soc., 132, 2887-2904.

The interface is simplified to a single line of code in the end user's Python scripts, making implementation of the algorithm in their research analyses very easy. The software package also interfaces well with other open source radar packages, such as the [Python ARM Radar Toolkit (Py-ART)](<https://github.com/ARM-DOE/pyart>). Simple visualization (including vector and contour plots) and save/load routines (to preserve analysis results) are also provided.

PyTDA <https://github.com/nasa/PyTDA> software providing Python functions that will estimate turbulence from Doppler radar data. It is tested and working under Python 2.7 and 3.4.

DualPol <https://github.com/nasa/DualPol> This is an object-oriented Python module that facilitates precipitation retrievals (e.g., hydrometeor type, precipitation rate, precipitation mass, particle size distribution information) from polarimetric radar data. It leverages existing open source radar software packages to perform all-in-one QC and retrievals that are then easily visualized or saved using existing software.

CSU Radar Tools https://github.com/CSU-Radarmet/CSU_RadarTools Python tools for polarimetric radar retrievals.

This codebase was developed at Colorado State University by numerous people, including Brenda Dolan, Brody Fuchs, Kyle Wiens, Rob Cifelli, Larry Carey, Timothy Lang, and others.

Currently, fuzzy-logic-based hydrometeor identification, blended rainfall, DSD retrievals, and liquid/ice mass calculations are supported. There is also an algorithm that uses a finite impulse response (FIR) filter to process differential phase and calculate specific differential phase. Finally, there are some tools to do rudimentary QC on the data.

Appendix 3: Papers in press that used Py-ART

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1 https://github.com/ARM-DOE/pyart-roadmap/blob/master/reviews/concatinated_reviews.md
2 <https://github.com/nasa/MultiDop>
3 <https://github.com/openradar/TINT> (under development)
4 <https://github.com/ARM-DOE/>