A comparison of Galactic electron density models using PyGEDM

D.C. Price¹,²,³, C. Flynn², A. Deller²
¹International Centre for Radio Astronomy Research, Curtin University, Bentley WA 6102, Australia
²Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn VIC 3122 Australia
³Department of Astronomy, University of California Berkeley, Berkeley CA 94720

Abstract

Galactic electron density distribution models are crucial tools for estimating the impact of the ionised interstellar medium on the impulsive signals from radio pulsars and fast radio bursts. The two prevailing Galactic electron density models are YMW16 (Yao et al., 2017) and NE2001 (Cordes & Lazio, 2002). Here, we introduce a software package PyGEDM which provides a unified application programming interface (API) for these models and the YT20 (Yamasaki & Totani, 2020) model of the Galactic halo. We use PyGEDM to compute all-sky maps of Galactic dispersion measure (DM) for YMW16 and NE2001, and compare the large-scale differences between the two. In general, YMW16 predicts higher DM values toward the Galactic anticentre. YMW16 predicts higher DMs at low Galactic latitudes, but NE2001 predicts higher DMs in most other directions. We identify lines of sight for which the models are most discrepant, using pulsars with independent distance measurements. YMW16 performs better on average than NE2001, but both models show significant outliers. We suggest that future campaigns to determine pulsar distances should focus on targets where the models show large discrepancies, so future models can use those measurements to better estimate distances along those line of sight. We also suggest that the Galactic halo should be considered as a component in future GEDMs, to avoid overestimating the Galactic DM contribution for extragalactic sources such as FRBs.

Keywords: pulsars:general — stars:distances — ISM:structure — fast radio bursts

1 INTRODUCTION

Electron density models—models of the distribution of free electrons in the Galaxy—are routinely used to convert a dispersion measure (DM) along a given line-of-sight to an estimated distance, and vice versa. More broadly, they are used extensively in studies of Galactic composition, to describe scintillation and interstellar scattering, and to differentiate between extragalactic fast radio bursts (FRBs) and giant pulse emission from Galactic pulsars.

The DM is related to the integral free electron number density $n_e$ between Earth and a source at distance $d$. A frequency-dependent time delay, $\Delta t$, is imparted to electromagnetic radiation travelling through the ionised plasma along this sight line. For two observing frequencies, $\nu_1$ and $\nu_2$, the time delay is related to DM by:

$$DM \triangleq \int_0^d n_e \, dl = K \left( \frac{1}{\nu_1^2} - \frac{1}{\nu_2^2} \right)^{-1} \Delta t, \quad (1)$$

where in SI units, $K$ is given by

$$K = \frac{2\pi m_e c}{e^2} = 241.0331786(66) \, \text{GHz} \, \text{cm}^{-3} \, \text{pc} \, \text{s}^{-1}. \quad (2)$$

Here, $e$ is electron charge, $m_e$ is electron mass, and $c$ is the speed of light.$^1$

The impulsive, broad-band nature of radio pulsar emission means that observations of pulsars can provide measurements of DM—and thus the number of electrons along their sight line. If the electron density along the sight line is known, one can determine the distance to the pulsar, but this requires a Galactic electron density model (GEDM).

Over the years, GEDMs have been derived from independent distance measurements to pulsars (see §2). The prevailing GEDMs are NE2001 (Cordes & Lazio, 2002, 2003) and the Yao-Machester-Wang model (YMW16, ²Several approximations for $K$ are commonplace, and DM is also weakly sensitive to electron temperature and the presence of other, heavier charged particles; see the extensive discussion in Kulkarni (2020).
Yao et al., 2017). While YMW16 benefits from more recent data, and was shown in Yao et al. (2017) to give improved pulsar distance estimates, the NE2001 model is still in widespread use.

Further comparison of the two models was conducted in Deller et al. (2019) on a sample of 57 pulsars with VLBI parallax measurements, which indicated 1) the YWM16 model performs ‘somewhat better’ on high-latitude pulsars in the sample, 2) both models show large errors for some objects, and 3) both models tend to underestimate distances for the sample pulsars.

There is growing evidence from low-DM Fast Radio Bursts (FRBs) that the models may overestimate the Galactic DM contribution—despite neither model including a DM contribution arising from the Galactic halo. The CHIME/FRB Collaboration et al. (2019) report the repeating FRB180916.J0158+65 to have a DM of 349.2(3) pc cm$^{-3}$, very close to the 330 pc cm$^{-3}$ Galactic contribution as reported by YMW16. As FRB180916.J0158+65 has now been localized to a nearby spiral galaxy (Marcote et al., 2020), it is clear that YMW16 overestimates DM along this line-of-sight. Similarly, FRB 180430 is placed within the Galaxy by nearby spiral galaxy (Marcote et al., 2020), it is clear that YMW16 overestimates DM along this line-of-sight.

The CHIME/FRB Collaboration et al. (2019) have focused on high-latitude pulsars in the sample, 2) both models show large errors for some objects, and 3) both models tend to underestimate distances for the sample pulsars.

There is growing evidence from low-DM Fast Radio Bursts (FRBs) that the models may overestimate the Galactic DM contribution—despite neither model including a DM contribution arising from the Galactic halo. The CHIME/FRB Collaboration et al. (2019) report the repeating FRB180916.J0158+65 to have a DM of 349.2(3) pc cm$^{-3}$, very close to the 330 pc cm$^{-3}$ Galactic contribution as reported by YMW16. As FRB180916.J0158+65 has now been localized to a nearby spiral galaxy (Marcote et al., 2020), it is clear that YMW16 overestimates DM along this line-of-sight. Similarly, FRB 180430 is placed within the Galaxy by nearby spiral galaxy (Marcote et al., 2020), it is clear that YMW16 overestimates DM along this line-of-sight.

Clearly, there is room for improvement. Simple improvements to the models can be made by refitting parameters after including new independent pulsar distance measurements along individual sightlines, such as the large sample in Deller et al. (2019). Complementary to this approach—and the subject of this paper—qualitative analysis of how and where the models differ can help identify limitations within the models, and how these may be improved.

Improved estimates of Galactic DM contribution are of particular concern for FRB studies, as inaccurate estimates may limit the use of FRBs for cosmology. Kumar & Linder (2019) argues that for FRBs to be useful as a distance measure, bias in the noncosmological contributions to DM must be kept to under 0.6% of the total DM value: a challenging requirement.

Following Yamasaki & Totani (2020), the total DM for an extragalactic source can be expressed as a sum of four components:

$$D_{\text{Obs}} = D_{\text{ISM}} + D_{\text{halo}} + D_{\text{IGM}} + D_{\text{host}}$$

where $D_{\text{ISM}}$ is the contribution from the interstellar medium (ISM) in the Milky Way (MW) disk, $D_{\text{halo}}$ is the contribution from the extended Galactic halo, $D_{\text{IGM}}$ is that from the intergalactic medium (IGM), and $D_{\text{host}}$ is that from the host galaxy (including the source’s local environment). Note that on some sight lines, DM contributions from intervening galaxy halos may also need to be considered (e.g. Prochaska et al., 2019; Connor et al., 2020). Only the $D_{\text{IGM}}$ component—recently measured by Macquart et al. (2020)—is of interest for inferring cosmological distance; systematically overestimating or underestimating $D_{\text{ISM}}$ by using an inaccurate GEDM may thus bias or confound cosmological efforts.

In this paper, we present comparisons of the two models, made using a new Python package called PyGEDM that provides a unified interface to the YMW16 and NE2001 codes. Previous comparisons (e.g., Yao et al., 2017; Deller et al., 2019) have focused on how well the models predict the DM of pulsars with independent distance measurements; here, we compare their estimates on large angular scales.

This paper is organized as follows. In §2, we provide a brief overview of NE2001 and YMW16, and introduce the empirical relation between DM, $N_H$, and $A_V$. In §3, we introduce the PyGEDM package. In §4, comparisons of YMW16 and NE2001 are made, and model performance is compared against recent pulsar and FRB measurements. The paper concludes with a discussion of model limitations and recommendations for future measurements and improvements.

**2 GALACTIC ELECTRON DENSITY MODELS**

Forming a GEDM requires a set of distance measurements to pulsars paired with DM measurements; see Verbiest et al. (2012) for an overview. The signature of annual parallax is the most common model-independent distance measurement, and can be obtained using very long baseline interferometry (VLBI) imaging, or by fitting for variations in the arrival time of radio pulses in precision pulsar timing solutions. For pulsars within the Galactic disk, kinematic distance measurements can be made by use of 21-cm absorption spectra to convert radial velocities of HI clouds along the sight line to distances (however, this requires a Galactic rotation model). A third method is to use an association with nebulae, a globular cluster, or an optical counterpart.

Two of the earliest models of Galactic electron density were the LMT85 model (Manchester & Taylor, 1981; Lyne et al., 1985) and a model by Vivekanand & Narayan (1982), henceforth VK82. The LMT85 model was based upon kinematic distance measurements from HI absorption for 36 pulsars, and consisted only of three components: a thin disk, a term dependent upon height above the Galactic plane, and a model for the Gum Nebula. The VK82 model was similarly simple, but was derived independently using data from the Second Molonglo pulsar survey (Manchester et al., 1978).

These models were superseded by the TC93 model (Cordes et al., 1991; Taylor & Cordes, 1993), formed using 74 independent pulsar distance measurements. Measurements of interstellar scattering were also included in the model. As our understanding of Galactic structure advanced, and the number of independent distance measurements to pulsars increased, it became clear that
Figure 1. Electron density of NE2001 (left) and YMW16 (right) models, in the Galactic plane (\(z = 0\)). The NE2001 model extends to \(\pm 17\) kpc, whereas YMW16 extends to a radius \(\pm 30\) kpc. The Sun (red cross) is placed at \(x = 0, y = 8500\) pc, \(z = 0\) in NE2001, and at \(x = 0, y = 8300\) pc, \(z = 6\) pc in YMW16. The top panels show large-scale Galactic structure; differences in the spiral arm structure are visible. The bottom panels show the local ISM in a \(\pm 1\) kpc region centred about the Sun. The large ellipses in NE2001 (bottom left) correspond to a ‘local superbubble’ and ‘low density region’, which are not included in the YMW16 model. The local ‘clumps’ of NE2001, also not used in YMW16, are also visible as small circular regions. The local ISM in the YMW16 model (bottom right) has visibly fewer components; identifiable are the Gum nebula, local bubble, Loop I, and Carina-Sagittarius spiral arm.
an updated model was required to fix shortcomings in TC93.

2.1 NE2001

NE2001, as detailed in Cordes & Lazio (2002, 2003), and plotted in the left hand panels of Fig. 1, addressed many of the TC93 model’s shortcomings. NE2001 was formed from 112 pulsar distance measurements (i.e. independent of the GEDM), and 269 scattering measurements. Broadly, NE2001 assumes smoothly varying, large-scale components, then adds in perturbations by small-scale underdense or overdense regions. The model places the Galactic centre at a distance of 8.5 kpc from the Sun, and uses a right-handed Galactocentric coordinate system \((x, y, z)\) with the \(x\)-axis parallel to \(l=90^\circ\), and \(y\)-axis aligned toward \(l=180^\circ\). The Sun is located in the disk, at \((x=0, y=8500 \text{ pc}, z=0)\). The Galactic structure consists of a thin Gaussian annulus and thick axisymmetric disk, and spiral arms. Local components—the hot ‘local bubble’ surrounding the Sun, Gum Nebula, Vela Supernova Remnant (SNR), Loop 1, and a few other features—are also included in the model, along with a Galactic centre component. NE2001 also invokes so-called ‘clumps’ and ‘voids’, to account for sightlines where measurements suggest over- and under-dense regions respectively.

NE2001 uses an an iterative approach to parameter fitting (see §5 of Cordes & Lazio, 2003). Preliminary values from the TC93 were used, then parameters for large-scale components were fit by use of a likelihood function, followed by parameters from the local ISM; this process was then iterated.

2.2 YMW16

YMW16, as detailed in Yao et al. (2017), and plotted in the right hand panels of Fig. 1, has the significant advantage of 15 years of additional data to use when fitting their model. Over the intervening years, systematic issues with NE2001 were identified, which also informed the YMW16 model. Firstly, NE2001 systematically underestimates the \(z\)-distance for pulsars at high galactic latitude (Lorimer et al., 2006), due partly to the scale height for the thick disk being too small, which is evidenced by new observational measurements (Gaensler et al., 2008; Savage & Wakker, 2009). The NE2001 model was also found to overpredict distances for some local pulsars (Chatterjee et al., 2009).

YM16 uses 189 independent pulsar distance measurements, but unlike NE2001 does not make use of interstellar scattering measurements, arguing that scattering is generally dominated by a few regions along the path to a pulsar, so scattering measurements do not inform about large-scale structure.

In YMW16, the Sun is placed at \((x=0, y=8300 \text{ pc}, z=6 \text{ pc})\), which includes an offset from the Galactic plane as reported in Joshi et al. (2016). Like NE2001, YMW16 uses three major Galactic components. The first, an axisymmetric thick disk, is modelled in a similar fashion to NE2001. However, its thin disk component is modelled both radially and vertically with \(sech^2\) functions, and it uses a 4-spiral-arm model Hou & Han (2014) in contrast to the modified spiral pattern used in NE2001. Seven local features—the Local Bubble, regions of enhanced density nearby the Local Bubble, the Gum Nebula, Loop I (Berkhuijsen et al., 1971), a enhanced region in the Carina arm, and a low density pocket in the Sagittarius tangential region—are included in the YMW16 model, similar to NE2001. YMW16 also provides a models for the Magellanic clouds and IGM. Beyond these features, YMW16 rejects the use of voids and clumps for pulsar-specific optimization, arguing this is poor practice as it leads to overfitting. Further comparison of the features in the two models can be found in §5.2 of Yao et al. (2017).

Overall, the YMW16 model has 117 parameters: 35 parameters are fitted by using an optimization routine, with the other parameters fixed to values from the literature. Parameter fitting was performed using the PSWARM ‘particle swarm’ algorithm (see §4 of Yao et al., 2017).

2.3 Galactic halo models

YM16 and NE2001 do not model the DM contribution from the Galactic halo, \(\text{DM}_{\text{halo}}\). While modelling the halo is not necessary for pulsars within the Milky Way, a model of the halo is necessary for determining \(\text{DM}_{\text{host}}\) and \(\text{DM}_{\text{IGM}}\) extragalactic sources such as FRBs. Here, we provide a brief overview of estimates for \(\text{DM}_{\text{halo}}\), starting with a toy model where we assume baryons in the halo are distributed spherically and with uniform density out to the virial radius.

It is well established that the baryons residing in galaxies in the form of stars and cold or warm gas account for only a fraction of the baryons measured in the the \(\Lambda\)CDM model. These baryons are predominantly thought to reside in the IGM, but some are expected to reside within the virial radii of galaxies. The baryonic mass of the Milky Way that has been accounted for directly is \(\approx 7 \times 10^{10} M_\odot\) (Flynn et al 2006), while its dark matter halo has a mass order \(1.2 \times 10^{12} M_\odot\) and a virial radius of order 200 kpc (Wang et al 2015). Assuming the Milky Way has captured the cosmic fraction of baryons to dark matter \((\approx 0.15)\), we estimate \(\approx 1.3 \times 10^{11}\) hot baryons in the halo. The DM is then given by \(R_{\text{vir}} n_e\), where \(n_e\) is the electron number density. Taking \(M_B\) is the mass in baryons in the halo, \(m_p\) as the proton mass, and \(R_{\text{vir}}\) is the virial radius, the electron density \(n_e\) is given by \((M_B/m_p)/V\), where \(V = \frac{4}{3}\pi R_{\text{vir}}^3\). Inserting typical values yields \(\text{DM} = 30 \text{ pc cm}^{-3}\) for the Milky Way.

This toy model is broadly consistent with what is
found in hydrodynamical simulations of galaxy formation in a cosmological context. For example, Dolag et al. (2015) analyse a Milky Way-like galaxy from such simulations, find a range of DM in the (lumpy) halo of 40 to 70 pc cm$^{-3}$ somewhat more than the simple estimate of 30 pc cm$^{-3}$ above.

2.3.1 Halo DM estimates via diffuse gas

Prochaska & Zheng (2019) (henceforth PZ19) estimate $\Delta m_{\text{halo}}$ by fitting two components: $T \sim 10^4$ K gas (which they refer to as “cool”) and $T \sim 10^6$ K gas (referred to as “hot”):

$$\Delta m_{\text{halo}} = \Delta m_{\text{halo,cool}} + \Delta m_{\text{halo,hot}}.$$  \hspace*{2cm} (4)

For their cool component, they isolate high velocity clouds (HVCs) with velocities $>100$ km s$^{-1}$ from HI4PI data (HI4PI Collaboration et al., 2016), to produce a $N(H,\text{HVC}$ for HVCs only. These data are combined with column density measurements of $\text{Si II}$ and $\text{Si III}$ from the Richter et al. (2017) HVC survey, which are dominant ions of silicon at $T \sim 10^4$ K. PZ19 finds an average value of $\Delta m_{\text{halo,cool}} \approx 20$ pc cm$^{-3}$. For the hot component, PZ19 analyzes measurements of $\text{O VI}$ and $\text{O VII}$ X-ray absorption spectra (Fang et al., 2015), and estimate that the ionized plasma revealed by these tracers adds a contribution $\Delta m_{\text{halo,hot}}=50–80$ pc cm$^{-3}$.

Das et al. (2021) (henceforth D20) use a similar approach to PZ19, but do not directly differentiate between the disk and halo. Instead, they model the overall Galactic DM contribution, $\Delta m_{\text{MW}}$, as a combination of four phases:

$$\Delta m_{\text{MW}} = \Delta m_{\text{cold}} + \Delta m_{\text{cool}} + \Delta m_{\text{warm}} + \Delta m_{\text{hot}},$$  \hspace*{2cm} (5)

where the four components refer to gas at $\sim 10^4$K, $10^4–10^7$K, $10^5–10^6$K, and $>10^7$K, respectively. Note that these designations differ from the temperature ranges typically used to refer to gas phases in the interstellar medium. Their “cold” and “hot” phases are found to be the primary contributors to $\Delta m_{\text{MW}}$, by at least an order of magnitude.

Combined, D20 find a median $\Delta m_{\text{MW}} = 64^{+26}_{-23}$ pc cm$^{-3}$, covering with a large scatter—two orders of magnitude, 33–172 pc cm$^{-3}$ (68% CI). This scatter is not predicted by smooth disk + halo models, and is supportive of the hot halo component being inhomogeneous and anisotropic.

Keating & Pen (2020) use gas profile models of the Galactic halo and incorporate constraints from X-ray observations to compute predicted values of $\Delta m_{\text{halo}}$. Values of $\Delta m_{\text{halo}}$ below 55 pc cm$^{-3}$ are favoured; however predictions for models allowed by X-ray constraints span more than an order of magnitude, reaching as low as 6 pc cm$^{-3}$.

2.3.2 Halo DM estimates via pulsars and FRBs

Another way to estimate the halo DM is to use pulsars at high galactic latitudes and in the Magellanic clouds. The clouds are sufficiently distant ($\sim 50$ kpc) that most of the DM in an NFW-like distribution of hot Magellanic clouds is within their Galactocentric radii (Navarro et al., 1997). Pulsars have a range of DMs in the Large Magellanic Cloud (LMC) from 65 to 200 pc cm$^{-3}$ (using data available in PSRCAT$^2$; Manchester et al., 2005). Assuming that the lower DM value of 65 pc cm$^{-3}$ represents pulsars least affected by the LMC’s own ISM, and that 50 pc cm$^{-3}$ of this is due to the disk ISM in the direction of the LMC (as estimated by both the NE2001 and YMW16 models), this yields a lower limit on the halo DM (in this direction) of approximately 15 pc cm$^{-3}$.

Platts et al. (2020) have made a similar analysis using the DMs of Galactic pulsars combined with the DMs of published FRBs, introducing a kernel density estimation technique to find lower and upper bounds for $\Delta m_{\text{halo}}$. They place a constraint of $-2 < \Delta m_{\text{halo}} < 123$ pc cm$^{-3}$ (95% C.I.), assuming a spherical distribution of the baryons. Tighter constraints may be derived using the Platts et al. (2020) framework as the sample of FRBs grows, and in particular as more low DM (i.e. nearby) FRBs are found.

A summary table of estimates for different model approaches is given in Tab. 1.

2.3.3 YT20

Observational support that a simple symmetric spherical halo model is inadequate comes from X-ray observations of diffuse halo (e.g. Nakashima et al., 2018). They favour a two component model: a spherical component extending up to 200 kpc, and a compact disk-like component that is geometrically distinct from the thick disk in ISM models.

Yamasaki & Totani (2020) (henceforth YT20) provide a two-component model fit to observations of diffuse X-ray emission. YT20 predicts $\Delta m_{\text{halo}}$ to be 30–245 pc cm$^{-3}$ over the whole sky, with a mean of 43 pc cm$^{-3}$.

The YT20 model consists of a spherical halo that extends to the virial radius (200 kpc), and a compact disk-like component. This disk-like component is differs in physical properties (i.e. temperature and geometrical shape) from the ISM’s thick disk, as included in NE2001 and YMW16. An all-sky map of the YT20 model is shown in Fig. 2.

While the gas distribution of the halo disk-like component overlaps with the ISM thick disk component, the YT20 authors argue it is reasonable to add the DM prediction from YMW16/NE2001 to estimate the total Galactic DM budget:

$$\Delta m_{\text{MW}} = \Delta m_{\text{YT20}} + \Delta m_{\text{YMw16}}.$$  \hspace*{2cm} (6)

$^2$http://www.atnf.csiro.au/research/pulsar/psrcat
Table 1 Summary of halo DM contribution from model estimates. Note Das et al. (2021) estimate is for the full Galactic DM contribution, DM$_{\text{MW}}$.

| Halo model                  | DM$_{\text{halo}}$ (pc cm$^{-3}$) | DM$_{\text{MW}}$ (pc cm$^{-3}$) |
|-----------------------------|-----------------------------------|----------------------------------|
| Baryon count estimate       | 30                                | -                                |
| LMC pulsar constraint       | >15                               | -                                |
| Dolag et al. (2015)         | 40–70                             | -                                |
| Prochaska & Zheng (2019)    | 70–100                            | -                                |
| Yamasaki & Totani (2020)    | 30–245                            | -                                |
| Platts et al. (2020)        | −2–123                            | -                                |
| Keating & Pen (2020)        | 6–55                              | -                                |
| Das et al. (2021)           | -                                 | 33–172                           |

However, as the gas distribution of the ISM thick disk and YT20 disk-like component overlap, GEDM models may overestimate the density of the thick disk; adding YT20 and YW16 estimates of DM may result in an overestimate for DM$_{\text{MW}}$.

Currently, YT20 is the only halo model with multiple components, giving rise to direction-dependent DM estimates. We provide an interface to YT20 as part of PyGEDM.

3 PYGEDM

We have developed a Python package, PyGEDM, which provides access to the NE2001 and YMW16 models of the ISM, and YT20 model of Galactic halo. Unit and coordinate conversions are handled using the Astropy package (Astropy Collaboration et al., 2013), and Healpy (Zonca et al., 2019) is used to generate all-sky maps. The PyGEDM code is open source and freely available online.

PyGEDM can be installed via the Python package manager with a single command (`pip install pygedm`), and build files are provided for the Docker containerization platform. A test suite is included to ensure code output is consistent with the YMW16 and NE2001 online interfaces. Searchable online documentation of the PyGEDM API is provided at https://pygedm.readthedocs.io.

PyGEDM provides a unified application programming interface (API) in Python, with the intention that it can be used as an upstream dependency for other projects. By doing so, changes to PyGEDM—for example, the addition of new GEDMs—can be immediately leveraged by downstream projects and data analysis codes. An example use case is for population synthesis codes such as FRBPOPPY\(^5\) (Gardenier et al., 2019) and PSrPoppPy\(^6\) (Bates et al., 2014), for FRB and pulsars respectively. These codes currently wrap a pre-compiled version of the NE2001 model. PyGEDM is used by FRUITBAT\(^7\) (Batten, 2019), which computes the redshift of FRBs for given cosmological models.

Both the YMW16 and NE2001 codes are written in performant, statically-compiled languages (C and Fortran, respectively). Python provides methods to interface with both C and Fortran code; in PyGEDM we use pybind11\(^8\) to interact with compiled library versions of the code. pybind11 is a library that exposes Python types in C++, and vice versa.

3.1 An interface to NE2001 using f2c and pybind11

Compiling the NE2001 code requires a Fortran compiler such as gfortran. To provide an interface to NE2001 via pybind11, and to avoid the need for a Fortran compiler, we used the f2c Fortran to C conversion program to convert the NE2001 codebase to C. While NE2001 is mostly compliant with the Fortran 77 standard, some reordering of statements was required to satisfy the f2c utility. The converted C code is available within the PyGEDM repository.

Before deciding on using f2c and pybind11, we used the f2py utility—part of the Numpy package (van der Walt et al., 2011)—to generate compiled extension modules that can be used in Python. This required adding special comment lines defined by f2py to the NE2001 Fortran code, which the Fortran compiler ignores but inform f2py whether arguments are meant as inputs, outputs, or both. When the PyGEDM Python package is installed, a Fortran compiler is called to compile NE2001 code, then f2py is run to compile Python-compatible shared objects. However, we found that this approach was not portable across different architectures and systems. As of writing, there is no native Fortran compiler for the Apple Silicon M1 architecture, and several users reported that installing PyGEDM via pip install pygedm did not work. We also found issues setting up continuous integration (CI) testing with Fortran, and hence ultimately abandoned this approach.

Using f2c-converted C code alleviates issues with Fortran compilers, but adds a requirement that the user has the f2c.h header and corresponding library installed. We find pybind11 to be more robust and easier to debug during installation of the Python package. The pybind11 approach also allows a more Pythonic API: the C++ `std::map` container is presented as a `dict` to Python. We use this to return a dictionary of key-value pairs when the C++ function is called.

Other open-source codes to allow Python access

\(^3\)https://github.com/FRBs/pygedm
\(^4\)https://www.docker.com
\(^5\)https://davidgardenier.github.io/frbpoppy/html/index.html
\(^6\)https://github.com/samb88/PSrPoppPy
\(^7\)https://github.com/abatten/fruitbat
\(^8\)https://pybind11.readthedocs.io/
to NE2001 are available. pyne2001\textsuperscript{9} calls the NE2001 executable and parses the resulting text output; this approach requires no changes to the Fortran code, but is slower than access via pybind11. The FRBs/NE2001\textsuperscript{10} code is a pure-Python reimplementation of the NE2001 code, not guaranteed to give identical results to the Fortran NE2001 code, and is considerably slower. The FrbPoppy and PsrPoppy codes compile NE2001 as a shared library, and then access it via Python ctypes.

We tested the speed of these approaches by installing all software within a Docker container, and then calling the relevant Python API to calculate the DM for a point 10 kpc away in the direction of the Galactic centre (\( b=0 \), \( l=0 \)). The Docker container was run on a Macbook Pro laptop (2020) with the Apple Silicon M1 chip, and the \%timeit magic function was used in an iPython shell to find the average runtime. We found the raw ctypes method to be the fastest at \( \sim 110\mu s \) per call, with our pybind11 approach taking \( \sim 790\mu s \). We attribute the overhead to the construction of the \texttt{std::map}, and conversion to Astropy quantities. pyne2001 is roughly 70 times slower than the ctypes approach, at \( \sim 7.96\) ms. Finally, the pure Python ne2001 implementation takes \( \sim 2.6s \): several orders of magnitude slower.

Although speed is important in some use cases, code maintainability, adaptability, and usability are also important considerations. While our approach is slower than using raw ctypes, overhead within Python, such as attribute lookup for variables within for loops, is likely to be the main bottleneck for most programs using PyGEDM. An approach to speed up loops over multiple lines of sight would be to move the loop into C++, which could be achieved via the built-in support for Numpy arrays in pybind11.

### 3.2 An interface to YMW16 and YT20

As YMW16 is written in C, only minor changes to the underlying code were required in order to create Python bindings using pybind11. We added a \texttt{main.cpp} file, in which the pybind11 module is defined. As with the NE2001 interface, we modified the YMW16 API to return \texttt{std::map} containers, which are presented in Python as dictionaries of key-value pairs.

The YT20 code in PyGEDM is adapted from \texttt{DM\_halo\_yt2020\_numerical.py}, provided by S. Yamasaki. As there were no extra dependencies, integration with PyGEDM was straightforward; some minor changes to coding style were made for uniformity.

---

\textsuperscript{9}https://github.com/v-morello/pyne2001

\textsuperscript{10}https://github.com/FRBs/ne2001

---

### 3.3 The PyGEDM API

The PyGEDM code provides the following methods:

- \texttt{dm\_to\_dist} – Convert a DM to a distance for a given line-of-sight in Galactic \((l, b)\) coordinates (NE2001 and YMW16).
- \texttt{dist\_to\_dm} – Convert a distance to a DM for a given line-of-sight (NE2001 and YMW16).
- \texttt{calculate\_electron\_density\_xyz} – Evaluate the electron density at a given Galactocentric \((x, y, z)\) coordinate (NE2001 and YMW16).
- \texttt{calculate\_electron\_density\_lbr} – Evaluate electron density at a given distance along line-of-sight in Galactic coordinates \((l, b)\), to a distance \(r\) (NE2001 and YMW16).
- \texttt{generate\_healpix\_dm\_map} – Generate an all-sky healpix map for a given distance \(r\) (NE2001, YMW16 and YT20).
- \texttt{calculate\_halo\_dm} – Compute \(D\_\text{halo}\) for a given \((l, b)\) pointing (YT20).
- \texttt{convert\_lbr\_to\_xyz} – Convert Galactic \((l, b, r)\) coordinates to Galactocentric \((x, y, z)\) coordinates (NE2001 or YMW16 – the two models place the Galactic centre at different distances).

Selection between YMW16, NE2001 and YT20 models is done by use of a method argument. We envisage adding support for future models as they become available.

### 3.4 Containerization

Docker is an open-source containerization platform, which is used to package up code and its dependencies into a standardized executable that can be built and deployed in a reproducible way. As part of the PyGEDM repository, we provide a Dockerfile, from which a Docker container for PyGEDM can be generated.
We provide a standalone web application for PyGEDM against the online interfaces at https://www.nrl.navy.mil/rsd/RORF/ne2001/ (NE2001, now defunct), and https://www.atnf.csiro.au/research/pulsar/ymw16/ (YMW16). To ensure future development does not alter code output, we wrote unit tests using pytest that check code output against known correct values. We have setup continuous integration (CI) testing using Github actions to automatically run the unit tests that check code output against known correct values. We have not attempted to write unit tests for the code repository. PyGEDM is covered by unit tests (i.e. 100% code coverage). Full coverage ensures that all functions are tested for correctness. We have not attempted to write unit tests for the underlying NE2001 or YMW16 code, but suggest that future GEDMs should do so as a matter of course.

3.5 Integration testing

Neither NE2001 or YMW16 are supplied with a testing framework, so we tested the output of PyGEDM against the online interfaces at https://www.nrl.navy.mil/rsd/RORF/ne2001/ (NE2001, now defunct), and https://www.atnf.csiro.au/research/pulsar/ymw16/ (YMW16). To ensure future development does not alter code output, we wrote unit tests using pytest that check code output against known correct values. We have setup continuous integration (CI) testing using Github actions to automatically run the unit tests whenever code is pushed to the PyGEDM repository.

Code coverage—a report of what parts of code are executed by the tests—is analysed using Codcov.io for all Python code in PyGEDM; all Python code is covered by unit tests (i.e. 100% code coverage). Full coverage ensures that all functions are tested for correctness. We have not attempted to write unit tests for the underlying NE2001 or YMW16 code, but suggest that future GEDMs should do so as a matter of course.

3.6 PyGEDM web application

We provide a standalone web application for PyGEDM in the /app directory of the code repository. This application can be used for estimation of DM along a line of sight to a given distance, and vice versa. The contribution of both NE2001 and YMW16 models as a function of DM (or distance) is shown graphically along the line of sight.

The application uses plotly and dash-labs to create the website interface, which is served using the gunicorn web server. A Dockerfile is provided to build and run the web application.

4 COMPARISON OF YMW16 AND NE2001 MODELS

Fig. 4 shows all-sky images made from YMW16 and NE2001, made using PyGEDM and plotted using the HEALPY package. Averaged across all pixels, the NE2001 model returns a mean DM of 107.9 pc cm$^{-3}$ and median 55.3 pc cm$^{-3}$ when evaluated out to its 17 kpc extent. The YMW16 model returns 110.6 pc cm$^{-3}$ and 48.7 pc cm$^{-3}$, respectively, when evaluated out to 30 kpc. That is, NE2001 reports a median DM$_{SM}$ contribution 1.14× higher than YMW16. There is, however, a strong dependence on Galactic latitude. At low latitudes ($|b| < 2^\circ$), YMW16 predicts larger distances than NE2001, whereas at high latitudes YMW16 predicts smaller distances (Fig. 5).

As apparent in Fig. 4, at 1 kpc large fractional differences between the two models are returned at the location of NE2001 clumps, with YMW16 in excess along most lines of sight at low Galactic latitudes, corresponding to features such as the Gum nebula, local bubble, Loop I, and NE2001’s low density region.

At 8.5 kpc (i.e. the distance to the Galactic centre), it becomes apparent that YMW16 predicts higher DM values away from Galactic centre ($|l| < 90^\circ$). YMW16 predicts higher DMs at low latitudes, but NE2001 predicts higher DMs in most other directions. These general trends remain out to 30 kpc (lower panels).

We may also compare model predictions for pulsar distance to GEDM-independent distance measurement. Fig. 6 shows histograms of log($D_{\text{measured}}/D_{\text{model}}$), the ratio of measured distance to model prediction, for the 189+57 measurements (left panels), and for the PSR$\pi$ sample (right panels). Corresponding Gaussian fits are also plotted, showing that the log transform has normalised the data. From Eq. 7, treating the error term as $\varepsilon_i = \mu \pm N\sigma$, where $\sigma$ and $\mu$ are the standard deviation and expected value of the Gaussian fit, and $N$ is the number of standard deviations used in confidence interval, we find:

$$D_{\text{model},i} e^{\mu-N\sigma} \leq D_{\text{measured},i} \leq D_{\text{model},i} e^{\mu+N\sigma} \tag{8}$$

As the distribution of $\varepsilon_i$ is not perfectly Gaussian, $3\sigma$ does not correspond to a 99% confidence interval (CI); as such we report CI percentages. For pulsars within the

---

11https://codecov.io
12https://plotly.com
13https://github.com/plotly/dash-labs

The fractional difference is defined as $(DM_{YM16} - DM_{NE2001})/DM_{YM16}$; negative values imply $DM_{NE2001} > DM_{YM16}$.
Figure 4. All-sky maps (Mollweide projection) in Galactic coordinates, showing DM along line of sight to 1 kpc (top), 8.5 kpc (middle), and 30 kpc (bottom), for the YMW16 (left) and NE2001 (center) models. Fractional difference between the two maps is shown on the right.
189+57 sample, using 3σ we find that 86% of YMW16 distance estimates lie between 0.35–2.76 × D_measured; for NE2001, 87% of distance estimates lie between 0.28–3.48 × D_measured. That is, YMW16 performs better on average.

Nonetheless, this analysis of all 189+57 pulsars is biased toward YMW16 as it includes the pulsars used in the creation of YMW16. As discussed in Deller et al. (2019), the PSRπ pulsars can be used as an independent test, as they were not used in the creation of either model. When considering only the PSRπ sample (Fig. 6, right panels), 86% of NE2001 distance estimates lie within 0.12–4.10 × D_measured, with a mean offset of 0.70; i.e. NE2001 systematically underestimates distances. YMW16, in comparison, has a mean offset of 0.85; however, the Gaussian fit has several significant outliers. The 3σ range for YMW16 is 0.22–3.33 × D_measured, with 82% of estimates within this range.

The most discrepant pulsars (where the model DM estimate differs by more than an order of magnitude) for the two GEDMs are summarized in Tab. 2. Of these:

- J0248+6021 is located in/behind a nebula toward the Galactic anticenter; both models greatly overestimate its distance.
- J0942–5552 and J1017–7156 are located toward the Gum nebula (l ∼ 264°). NE2001 places J0942–5552 significantly further away, and both models overestimate distance to J1017–7156.
- J1735–0724, and J1741–0840 are located toward Loop I.
- J1623–0908 lies behind a the HII Region Sh 2-27 (Ocker et al., 2020).
- J1745–3040 is located toward the Galactic center.

The two pulsars J1735–0724 and J1741–0840 are particularly poorly estimated by YMW16. The discrepancy appears to be due to excess electron density below 200 pc, due to the contribution of Loop I. The discrepancy suggests that either the electron density of Loop I is overestimated and/or that Loop I is further away than modeled. We highlight this as of particular interest, given that the distance to Loop I is contentious (e.g. Bland-Hawthorn & Cohen, 2003; Shchekinov, 2018; Dickinson, 2018).

We find some spatial clustering of pulsars for which the GEDMs poorly predicts pulsar distance (Fig. 7). In Fig. 7, pulsars where distances are over- or underestimated by more than 1.5 × are plotted on top of a map of DM_{MW} (YMW16 with YT20 halo added). Pulsars toward the antiflare are more likely to have their distances overestimated, as are those in the direction of Loop I (for YMW16 only) and the Gum nebula. To look for trends, we took the subset of pulsars with distance estimates discrepant by more than 1.5 × (Fig. 7), and binned them by latitude, longitude, and distance. We find:

- Pulsars between 60° < l < 90° are more likely to have their distances underestimated for both models.
- Pulsars between 120° < l < 180° are more likely to have distances overestimated for YMW16. NE2001 is likely to overestimate between 120° < l < 150°.
- Low Galactic latitudes (b < −15°) are likely to be underestimated by YMW16, but overestimated by NE2001.
- Pulsars with distances below 1 kpc are more likely to be underestimated by both models, whereas pulsars with distances between 1–3 kpc are likely to be overestimated.

We also plot FRBs with low DM excess (<50 pc cm⁻³) in Fig. 7, taken from FRBCAT\textsuperscript{15} on 2021-06-10 (Petroff et al., 2016), and the CHIME FRB Catalog 1 (The CHIME/FRB Collaboration et al., \textsuperscript{15}http://www.frbcat.org

\begin{table}[h]
\centering
\begin{tabular}{lccc}
\hline
Source & D_{meas} & D_{NE2001} & D_{YMW16} \\
\hline
J0248+6021 & 2000^{+260}_{-200} & 43459 & 25000 \\
J0942–5552 & 300^{+280}_{-200} & 3770 & 415 \\
J1017–7156 & 256^{+114}_{-60} & 2980 & 1807 \\
J1623–0908* & 1710^{+2050}_{-250} & 49998 & 25000 \\
J1735–0724* & 6680^{+8310.0}_{-5250.0} & 2261 & 213 \\
J1741–0840* & 3580^{+920}_{-550} & 2169 & 222 \\
J1745–3040 & 200^{+1200}_{-20} & 1913 & 2343 \\
J1912+2104* & 41020^{+377750}_{-35000} & 3960 & 3360 \\
\hline
\end{tabular}
\caption{Table of most significant outliers, where D_{model}/D_{measured}, the ratio of model prediction to measured distance, is below 0.1 or greater than 10. Bolded values indicate where one model notably better predicts the distance. Pulsars from the PSRπ sample are marked with an asterisk.}
\end{table}
2021). The combined DM$_{MW}$ map places two FRBs within the galaxy: FRB20180916B (previously named FRB180916J0158+65) (CHIME/FRB Collaboration et al., 2019) and FRB1808430 (Qiu et al., 2019). Both of these FRBs are at low latitudes on sight lines away from the Galactic centre. FRB20180916B has been shown to be extragalactic (Marcote et al., 2020); taken together with pulsar distance overestimates, one can conclude that YMW16 systematically overestimates on sight lines toward the Galactic anticentre. In contrast, NE2001 does not place any FRB within the Galaxy.

5 DISCUSSION

Both NE2001 and YMW16 have proven to be invaluable tools for conversion between DM values and distance estimates. In this article, we introduce PyGEDM, a Python package that provides a unified interface to NE2001, YMW16, and the YT20 GEDMs.

We used PyGEDM to quantitatively compare and contrast the NE2001 and YMW16 models, highlighting where their predictions differ. We also compare GEDM predictions to pulsar measurements, finding that YMW16 performs better on average than NE2001, but that both models show significant outliers. We highlight that distances to J1735−0724 and J1741−0840 are poorly estimated by YMW16, suggesting that Loop I may be further away than modelled. There is still debate as to whether Loop I is a local feature—as YMW16 assumes—or associated with the Fermi bubble above Galactic centre, or both (Dickinson, 2018; Shchekinov, 2018). Additionally, pulsars between $120^\circ < l < 180^\circ$ are more likely to have distances overestimated for YMW16. Taken together with FRB measurements, it is clear that YMW16 overestimates the overall Galactic DM contribution toward the Galactic anticentre.

Both NE2001 and YMW16 underestimate distance for pulsars in the PSR$\pi$ sample. As discussed in Deller et al. (2019), pulsars at high galactic latitudes are over-represented in PSR$\pi$, so it is not an unbiased sample. The median distance for pulsars in the sample is 2.5 kpc, whereas the median distance for pulsars with parallax measurement used in YMW16 is 1.1 kpc. Incorporating the PSR$\pi$ sample will improve next-generation GEDMs, particularly at high latitude.

More generally, new GEDM-independent pulsar distance measurements will provide tests of GEDMs and further data to use in modelling. We suggest that pulsar targets are chosen strategically, focusing on areas where the GEDMs give poor distance estimates; namely, toward the Galactic anticentre, Loop I, the Gum nebula, and at low Galactic latitudes.

Improving models of DM$_{halo}$ will be important for FRB-based cosmology experiments. Kumar & Linder (2019) argue that biases in any noncosmological contributions to DM must be kept to under 0.6%: a budget of only 15.6 pc cm$^{-3}$ for even the highest recorded DM of 2596.1 ± 0.3 pc cm$^{-3}$ (FRB160102, Bhandari et al., 2018). As such, future GEDMs should also ensure that their estimate of DM$_{ISM}$ does not contain contributions from the Galactic halo; or, a combined ISM and halo parameter could be fit to data. Currently, simply adding the YT20 to YMW16/NE2001 DM estimate likely overestimates the Galactic contribution for a given FRB.

Current GEDMs do not provide the user the tools to rerun parameter fitting with additional data or to add/modify features. We suggest that future GEDMs should provide such tools, so new measurements can be rapidly incorporated to improve the model.

Follow-up campaigns toward repeating FRBs will result in long observations, upon which pulsar searches could be conducted. Searches for pulsars along or near FRB sight lines would allow more accurate determination of DM$_{ISM}$ toward the FRB. We suggest that such searches should be done as a matter of course, to improve our understanding of the ISM and help facilitate the emerging field of FRB cosmology.

6 ACKNOWLEDGEMENTS

We thank the authors of NE2001 (J. Cordes and J. Lazio), YMW16 (J. M. Yao, R. N. Manchester, N. Wang), YT20 (S. Yamasaki and T. Totani) and PZ19 (J. X. Prochaska and Y. Zheng) for email correspondence and providing these valuable models. A.T.D. is the recipient of an Australian Research Council Future Fellowship (FT150100415).
Figure 7. Location of FRBs with low DM excess (<50 pc cm\(^{-3}\)), plotted on top of total Galactic DM contribution (YMW16 + YT20). Also overlaid are pulsars where YMW16 distance is overestimated (gold ▲), or underestimated (cyan ▼) by more than 1.5×. The DM excess, in pc cm\(^{-3}\), for each FRB is shown in parentheses.

REFERENCES

Astropy Collaboration et al., 2013, A&A, 558, A33
Bates S. D., Lorimer D. R., Rane A., Swiggum J., 2014, MNRAS, 439, 2893
Batten A., 2019, The Journal of Open Source Software, 4, 1399
Berkhuijsen E. M., Haslam C. G. T., Salter C. J., 1971, A&A, 14, 252
Bhandari S., et al., 2018, MNRAS, 475, 1427
Bland-Hawthorn J., Cohen M., 2003, ApJ, 582, 246
CHIME/FRB Collaboration et al., 2019, ApJ, 885, L24
Chatterjee S., et al., 2009, ApJ, 698, 250
Connor L., et al., 2020, MNRAS, 499, 4716
Cordes J. M., Lazio T. J. W., 2002, arXiv e-prints, pp astro-ph/0207156
Cordes J. M., Lazio T. J. W., 2003, arXiv e-prints, pp astro-ph/0301598
Cordes J. M., Weisberg J. M., Frail D. A., Spangler S. R., Ryan M., 1991, Nature, 354, 121
Das S., Mathur S., Gupta A., Nicastro F., Krongold Y., 2021, MNRAS, 500, 655
Deller A. T., et al., 2019, ApJ, 875, 100
Dickinson C., 2018, Galaxies, 6, 56
Dolag K., Gaensler B. M., Beck A. M., Beck M. C., 2015, MNRAS, 451, 4277
Fang T., Buote D., Bullock J., Ma R., 2015, ApJS, 217, 21
Gaensler B. M., Madsen G. J., Chatterjee S., Mao S. A., 2008, PASA, 25, 184
Gardenier D. W., van Leeuwen J., Connor L., Petroff E., 2019, A&A, 632, A125
HI4PI Collaboration et al., 2016, A&A, 594, A116
Hou L. G., Han J. L., 2014, A&A, 569, A125
Joshi Y. C., Dambis A. K., Pandey A. K., Joshi S., 2016, A&A, 593, A116
Keating L. C., Pen U.-L., 2020, MNRAS, 496, L106
Kulkarni S. R., 2020, arXiv e-prints, p. arXiv:2007.02886
Kumar P., Linder E. V., 2019, Phys. Rev. D, 100, 083533
Lorimer D. R., et al., 2006, MNRAS, 372, 777
Lyne A. G., Manchester R. N., Taylor J. H., 1985, MNRAS, 213, 613
Macquart J. P., et al., 2020, Nature, 581, 391
Manchester R. N., Taylor J. H., 1981, AJ, 86, 1953
Manchester R. N., Lyne A. G., Taylor J. H., Durdon J. M., Large M. I., Little A. G., 1978, MNRAS, 185, 409
Manchester R. N., Hobbs G. B., Teoh A., Hobbs M., 2005, AJ, 129, 1993
Marcote B., et al., 2020, Nature, 577, 190
Nakashima S., Inoue Y., Yamasaki N., Sofue Y., Kataoka J., Sakai K., 2018, ApJ, 862, 34
Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
Ocker S. K., Cordes J. M., Chatterjee S., 2020, ApJ, 897, 124
Petroff E., et al., 2016, PASA, 33, e045
Platts E., Prochaska J. X., Law C. J., 2020, ApJ, 895, L49
Prochaska J. X., Zheng Y., 2019, MNRAS, 485, 648
Prochaska J. X., et al., 2019, Science, 366, 231
Qiu H., Bannister K. W., Shannon R. M., Murphy T.,
Bhandari S., Agarwal D., Lorimer D. R., Bunton J. D.,
2019, MNRAS, 486, 166
Richter P., et al., 2017, A&A, 607, A48
Savage B. D., Wakker B. P., 2009, ApJ, 702, 1472
Shchekinov Y., 2018, Galaxies, 6, 62
Taylor J. H., Cordes J. M., 1993, ApJ, 411, 674
The CHIME/FRB Collaboration et al., 2021, arXiv e-prints, p. arXiv:2106.04352
Verbiest J. P. W., Weisberg J. M., Chael A. A., Lee K. J., Lorimer D. R., 2012, ApJ, 755, 39
Vivekanand M., Narayan R., 1982, Journal of Astrophysics and Astronomy, 3, 399
Yamasaki S., Totani T., 2020, ApJ, 888, 105
Yao J. M., Manchester R. N., Wang N., 2017, ApJ, 835, 29
Zonca A., Singer L., Lenz D., Reinecke M., Rosset C.,
Hivon E., Gorski K., 2019, The Journal of Open Source Software, 4, 1298
van der Walt S., Colbert S. C., Varoquaux G., 2011, Computing in Science and Engineering, 13, 22