How does the grouping scheme affect the Wiener Filter reconstruction of the local Universe?

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ABSTRACT

High quality reconstructions of the three dimensional velocity and density fields of the local Universe are essential to study the large Local Scale Structure. In this paper, the Wiener Filter reconstruction technique is applied to galaxy radial peculiar velocity catalogs to understand how the Hubble constant ($H_0$) value and the grouping scheme affect the reconstructions. While $H_0$ is used to derive radial peculiar velocities from galaxy distance measurements and total velocities, the grouping scheme serves the purpose of removing non linear motions. Two different grouping schemes (based on the literature and a systematic algorithm) as well as five $H_0$ values ranging from 72 to 76 km s$^{-1}$ Mpc$^{-1}$ are selected. The Wiener Filter is applied to the resulting catalogs. Whatever grouping scheme is used, the larger $H_0$ is, the larger the infall onto the local Volume is. However, this conclusion has to be strongly mitigated: a bias minimization scheme applied to the catalogs after grouping suppresses this effect. At fixed $H_0$, reconstructions obtained with catalogs grouped with the different schemes exhibit structures at the proper location in both cases but the latter are more contrasted in the less aggressive scheme case: having more constraints permits an infall from both sides onto the structures to reinforce their overdensity. Such findings highlight the importance of a balance between grouping to suppress non linear motions and preserving constraints to produce an infall onto structures expected to be large overdensities. Such an observation is promising to perform constrained simulations of the local Universe including its massive clusters.

Key words: Techniques: radial velocities, Cosmology: large-scale structure of universe, Methods: numerical, Galaxies: groups

1 INTRODUCTION

On large scales, where the gravity prevails, the Universe is homogeneous and isotropic enough for the observed velocity field to reflect the evolution of the Large Scale Structure (LSS) and the total underlying mass (i.e. both baryonic and dark) distribution. Therefore, to study the formation and evolution of the LSS, the analysis of observational radial peculiar velocities plays a major role (e.g. Dekel 1994; Strauss & Willick 1995; Willick 1999; Dekel & Ostriker 1999). Consequently, several techniques have been developed to analyze the observed velocity datasets renewing the effort to measure them (e.g. Mathewson et al. 1992; Nusser & Davis 1995; Willick 1997; da Costa et al. 1998; Colless et al. 2001; Springob et al. 2007; Tully et al. 2008; Said et al. 2014; Tully et al. 2016) and leading to numerous studies (e.g. Zaroubi et al. 1997; Theureau et al. 1998; Courtois et al. 2012; Rathaus et al. 2013; Watkins & Feldman 2014; Hoffman et al. 2015, 2016). In particular, algorithms have been built to reconstruct from the sparse radial observational datasets, the three dimensional distribution of matter and the three dimensional velocity field (e.g. POTENT, Wiener Filter, VIRBIUS, respectively Dekel et al. 1995; Zaroubi et al. 1999; Lavaux 2016). Assuming a cosmological model as a prior, these methods are able to produce density and velocity fields of the local Universe on grids using for sole observational information the sparse and noisy radial peculiar velocity datasets.

In this paper, we focus on the Wiener Filter (WF) algorithm Zaroubi et al. 1999. This technique is very straightforward and Appendix A gives detailed equations. Briefly, based on correlation functions, derivation of matrices and their inverse, the Wiener Filter permits calculating readily the density and velocity fields assuming as a prior the power spectrum of a given cosmological model. While correlation functions are obtained with the power spectrum, the correlation vectors are derived with radial peculiar velocities called ‘the constraints’. These latter must be of high quality to allow exquisite reconstructions of the local Universe. Since the Wiener Filter is a linear minimal variance estimator, removing non linear motions in the observational catalogs seems primordial. A grouping scheme permits gathering galaxies that belong to a single cluster or group into one point. Subsequently, it produces one linear constraint (one position and radial peculiar velocity) against several non linear constraints that would damage the reconstruction obtained with the Wiener Filter. We thus seek to understand the impact of the chosen grouping scheme applied to the observational constraints on the resulting reconstructions. In addition, in view of the recent concerns and discrepancies regarding the Hubble constant value (see Jackson 2013 for a review), we wish to study also the differences between reconstructions obtained with observational catalogs derived...
using different Hubble constant values. The Hubble constant permits
indeed converting distances in $h^{-1}$ Mpc units and most importantly it
allows us to derive galaxy peculiar velocities from galaxy total veloc-
ties and distance measurements. Constraints are derived from the sec-
ond sparse and noisy observational distance dataset of the Cosmicflows
project\footnote{1} \cite{Tully+2013}.

To summarize, this paper aims at determining the variance of the
WF reconstruction with respect to the Hubble constant and grouping
scheme choices. The final goal is to select the best choices to build
constrained initial conditions of the local Universe within the CLUES\footnote{2} collaboration \cite{gottlober2010}. To study in detail our cosmic en-
virement, the resulting performed simulations should resemble the lo-
cal Universe down to the clusters. In particular, we expect to optimize
the reproduction of the local massive clusters that have been slightly
under massive so far, if not for the Virgo cluster \cite{Sorce+2016,Tempel+2016}.
These constrained simulations are the
starting point of several projects to study the local Universe in detail, to
understand our local environment and to compare it with observations.

This paper starts with a section describing the observational cat-
alog of radial peculiar velocities or more precisely of galaxy direct
distance measurements and the two grouping schemes compared here
\cite{Tully-private, Tempel+2016}. In a subsequent section, the Wiener Filter algorithm is applied to the observational cat-
alogue with the different schemes and applying different Hubble constant numerical values. First, the effect of the Hubble constant on
the reconstructed velocity and overdensity fields are studied then, the
impact of the grouping scheme on the reconstructed fields is analyzed in
detail. An additional analysis made after minimizing the biases in
the observational catalogs permits tempering the results. A conclusion
presenting the best strategy for the next step (building constrained ini-
tial conditions) closes the paper.

2 GROUPING & RECONSTRUCTION TECHNIQUES

2.1 The Catalog

The second generation catalog built by the Cosmicflows collabora-
tion is a publicly released catalog of radial peculiar velocities
or more precisely of direct distance measurements. Published
in \cite{Tully+2013}, it contains more than 8,000 galaxy direct dis-
tance estimates. These measurements come mostly from the Tully-
Fisher \cite{TullyFisher1977} and the Fundamental Plane \cite{CepfFreedman2001}, Tip of the Red Giant
Branch \cite{Lee+1993}, Surface Brightness Fluctuation \cite{Tony+2001}, supernovae of type Ia
\cite{Jha+2007} and other miscellaneous methods also contribute to this large dataset though to a minor ex-
tent (~ 12% of the data). Using $H_0 = 75.2 \approx 100h$ km s$^{-1}$ Mpc$^{-1}$ (the value given by \cite{Tully+2013}),
it extends up to about 250 $h^{-1}$ Mpc and about 50% of the data are within $70$ $h^{-1}$ Mpc and 90% within $160$ $h^{-1}$ Mpc. In a companion paper \cite{Sorce+2017}, we have shown that, in absence of a complete catalog and provided that it is
properly grouped, the sampling of this catalog is optimal for Wiener Filter reconstructions with respect to uniformly distributed catalogs or catalogs of sole clusters. The goal is then to track the impact of the
grouping technique on the resulting reconstructions.

2.2 The Grouping Schemes

A grouped version designed by Tully, hereafter referred to as
Tully Grouping Scheme, and released via the Extragalactic Distance

\footnote{1} http://www.ipnl.in2p3.fr/projet/cosmicflows/
\footnote{2} https://www.clues-project.org/

Database was used to build the first generation of constrained initial
conditions that result in simulations resembling the local Uni-
verse down to $2 - 3$ $h^{-1}$ Mpc \cite{Sorce+2016}. However, clusters
reveal themselves to be under massive except for the Virgo cluster
\cite{Sorce+2016} thanks to the prior minimization of biases intro-
duced by \cite{Sorce+2016} that reduces the infall onto the local Volume,
leads the monopole of the velocity field to zero and gaussianizes the
distribution of observed radial peculiar velocities.

The difficulty resides in the definition of ‘group’ itself. If on the
simulation side, groups are well defined thanks to an access to the
entire 3D information, on the observational side, calling an ensemble
of galaxies a group constitutes a great challenge because of a re-
stricted access to the information. In observations, knowing precisely
the fraction of collapsed material becomes quite problematic. Still sev-
neral schemes have been developed to define groups within galaxy cat-
als. They mainly invoke Friends of Friends (FoF) like algorithms
based on projected separation, radial velocities and even luminosities
to identify what are called ‘groups’ of galaxies \cite{Huchra+1982,Geller+1983,Ramella+2002,Eke+2004,Yang+2008,Crook+2007,Makarov+2011,Lavaux+2014,Old+2014,Tempel+2014,Old+2015}.
This paper does not aim at scrutinizing in detail the methods
used to group catalogs. It aims at testing two recently released ver-
sions of groups for galaxies in the local Universe to understand
the differences in the reconstructions generated by two various grouping
schemes as described below:

- \cite{Tempel+2016} \ and \cite{Sorce+2016} introduced a new grouping method (hereafter Tempel Grouping scheme). This method is based on a widely used FoF
percolation method, where different linking lengths in radial (along the
line of sight) and in transversal (in the plane of the sky) directions are
used but the conventional FoF groups are refined using multimodal-
ity analysis. More precisely, \cite{Tempel+2016} use a model-based
clustering analysis to check the multimodality of groups found by the
FoF algorithm and they separate nearby/merging systems. In the
current paper, we use published catalogs of groups detected using this
new method.

- Tully Grouping scheme is based on literature groups and in that
respect is not a systematic scheme. Within 30 Mpc, groups are those
identified by \cite{Tully1987}, further away groups are those given in
the literature like Abell’s catalog \cite{Abell+1989}. Recently, \cite{Tully+2015} \ and \cite{Sorce+2017} published a more systematic way of deriving groups based on radii of second turn around and iterations. After comparisons, we find that the catalog grouped with this last scheme is an intermedi-
ate between the catalogs obtained with Tully and Tempel Grouping
schemes and as such will result in more mitigated conclusions would
we compare it to Tempel Grouping scheme. In addition, Tully Group-
ing scheme has been used so far with the second catalog to build con-
strained initial conditions. We thus stick to Tully Grouping scheme in
the rest of the paper.

\cite{Sorce+2016} and \cite{Tempel+2016} Grouping schemes provide the groups to which
the different galaxies that populate the second catalog of Cosmicflows
belong to as well as their total velocity (derived from the observed red-
shift). We note that the grouping schemes deliver groups built with a
complete down to a magnitude limit sample of galaxies. Then, galaxies
from the second catalog of Cosmicflows are distributed into these
groups and only the groups to which they belong are retained for fur-
ther use. The second catalog of Cosmicflows gives the individual dis-

\footnote{3} http://edd.ifa.hawaii.edu/
\footnote{4} Note that we reproduced the work with the 2015 Tully Grouping scheme and
found that it gives as expected intermediate results between Tully and Tempel
Grouping schemes.
tance modulus (µ) measurements of each galaxy and their uncertainty (σg). To determine the radial peculiar velocity of the groups and their position in real space (by opposition with redshift space), we proceed as follows (Tully private communication):

\[
\mu_g = \frac{\sum w \times \mu}{\sum w} ; \quad \sigma_{\mu g} = \sqrt{\frac{1}{\sum w}} \text{ where } w = \frac{1}{\sigma_g^2},
\]

\[
d_g = 10^{\frac{\mu_g - 25}{5}} ; \quad \sigma_{d_g} = \frac{\sigma_{\mu g} \times \log(10)}{5},
\]

\[
\nu_{pec g} = \nu_{tot g} - H_0 \times d_g ; \quad \sigma_{\nu_{pec g}} = \sigma_{d_g} \times d_g \times H_0,
\]

where the subscript ‘g’ stands for ‘grouped’ value and σ for the uncertainty of the given subscript value, d is the distance in real space, νtot is the total velocity of the galaxy/group and νpec is the radial peculiar velocity.

Table 1 reflects the resulting grouped catalogs after application of the two schemes. The first column shows interestingly that while Tully scheme results in more isolated galaxies (i.e. single position and peculiar velocity as constraint for the Wiener Filter algorithm), Tempel scheme gives less isolated galaxies but more groups (2344 against 910). Overall, Tully scheme is more aggressive than Tempel scheme. While on average, there is 4.5 distance measurements per group with Tully scheme, there is on average only 2.1 distance measurements per group with Tempel scheme. However, this difference could be due to the absence of group identification in Tully scheme when there is only one galaxy measurement. Indeed, summing in both cases the number of isolated galaxies and that of groups with only one measurement, the numbers become similar (4542 for Tully versus 4734 for Tempel). However, excluding groups with a single measurement, there is still on average more distance measurements per group with Tully scheme (7.8) than with Tempel scheme (4.1) confirming that Tully scheme groups more (number of groups with more than one measurement about twice smaller). In total, Tully scheme provides 5008 constraints against 5562 for Tempel scheme.

Table 2.3 The Wiener Filter Technique

We apply the Wiener Filter technique to the 10 catalogs obtained with the 5 different H0 values and the two grouping schemes using Planck power spectrum (Planck Collaboration et al. 2014) as a prior. One might argue that using a different H0 value to build the catalog of constraints and the cosmological prior could bias the results. Note that tests we made changing the prior (for instance using WMAP7 instead of Planck power spectrum) show that the prior has only a very small, thus negligible, impact on the reconstruction with respect to the parameters (grouping scheme and H0 in the observational data) tested in this paper. In other words, the variance between reconstructions obtained with different priors with all the other parameters fixed is much smaller than the variance between reconstructions produced with the same prior but changing H0 or the grouping scheme.

A box size of 500 h⁻¹ Mpc is retained as the adequate size to contain all the data-constraints. Note that from now on, the discussion will be led in h⁻¹ Mpc. Namely, once H0 has been chosen, every distance is converted in h⁻¹ Mpc such that H0=100h km s⁻¹ Mpc⁻¹. A grid size of 256³ cells permits a resolution about 2 h⁻¹ Mpc, the linear theory threshold, in agreement with the maximum resolution of the linear WF method. This ensures that differences observed between reconstructions are solely due to the tested parameters and not to non linear statistical fluctuations.

Additionally, non linear sigmas, explained in more detail in Appendix A, are essential to account for the residual of non linearities in the datasets. Indeed, even grouped catalogs still contain non linearities especially in high density regions with a poor sampling. The non linear sigmas correspond to a small additional smoothing applied to the constraints to compensate for their non linear component that cannot be accounted for directly by the linear Wiener Filter technique. They are simply added in quadrature to the uncertainties of the constraints. Non linear sigmas of the same order of magnitude (100-200 km s⁻¹) are found to be required for the different catalogs. Such similar values will prevent any difference due to a significant change in the smoothing. These non linear sigmas are essential to ensure that only significant differences remained visible between reconstructions obtained with various parameters.
3 WF RECONSTRUCTIONS

3.1 Tully Grouping: the results

The left panel of Figure 1 shows the reconstructed velocity and overdensity fields obtained with the catalog grouped with Tully scheme and using $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$. The right panel of the same figure presents the residual between the reconstructed fields obtained with two different $H_0$ values but the same grouping scheme. The effect is clear, the larger $H_0$ is, the greater the infall onto the local volume is. Namely, $H_0$ value impacts the tidal part of the velocity field. However, the overdensity field is not that much affected: there are only very small and sparse residual contours. It means that $H_0$ value influences only weakly the divergent part of the velocity field directly linked to the overdensity field. Note that this is the part of the velocity field used to build constrained initial conditions. The infall observed with larger value of $H_0$ impacts the global density of the local Volume. With a smaller value of $H_0$, not only the infall but also the global local density decrease: the spherical dashed contours on Figure 1 right indicate indeed that globally the reconstructed field obtained with the smallest value of $H_0$ has higher overdensity values than that obtained with the smallest value of $H_0$. Since an underdensity of the local Volume is not excluded (e.g. Keenan et al. 2013) while a large infall onto the local Volume is very unlikely, the smallest values of $H_0$ tested here might be preferred. However, in the last part of this section, we will temper this conclusion by applying the bias minimization scheme introduced in Section 2 and that needs to be applied to the observational catalog.

The first half of Table 2 summarizes the properties of the reconstructions obtained with Tully Grouping scheme and different $H_0$ values to support our findings based on Figure 1. On the one hand, it clearly shows that for large $H_0$ values, the infall is large: the monopole term of the velocity field is highly negative at large radii. The infall for larger $H_0$ values, deduced from the observed outflow in the subtraction of reconstructions obtained with increasing values of $H_0$ in the right panel of Figure 1 is confirmed. At both large and small radii, the dipole of the velocity field is on the other hand quasi-unchanged, in agreement with the fact that the overdensity (or divergent part of the velocity field) is quite unaffected by a change in $H_0$ value. These two points are visible in another form on Figure 2 where both monopole and dipole of the velocity field are shown at all radii. While the dipole is quite independent of $H_0$ value at all radii, the monopole tends to get smaller and smaller at all radii with $H_0$ getting larger and larger. On another aspect, the standard deviation of the overdensity and velocity fields increase slightly with the value of $H_0$.

While Table 2 shows properties of reconstructions obtained with different $H_0$ values independently of each other, the first third of Table 4 summarizes the comparisons between reconstructed fields obtained with different $H_0$ values but the same (Tully) grouping scheme. Standard deviation of the residual between two different $H_0$ reconstructed overdensity and velocity fields obviously increase with the difference between the two $H_0$ values but are quite stable for a given difference between the two $H_0$ values. In any case, the standard deviation of the residual is smaller than the standard deviation of the compared velocity and overdensity fields taken independently except when the reconstructed velocity field obtained with 76 km s$^{-1}$ Mpc$^{-1}$ is compared to that obtained with the smallest $H_0$ value (i.e. 72 km s$^{-1}$ Mpc$^{-1}$), namely when the separation between $H_0$ values, chosen for this paper, is maximal. Regardless, 76 km s$^{-1}$ Mpc$^{-1}$ seems to be a very unlikely value in light of the above observations.

3.2 Tempel Grouping: the results

Figure 3 shows the reconstructed velocity and overdensity field obtained with $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$, like in Figure 1 but with Tempel Grouping scheme. The observations made in the previous subsection still stand. Namely, $H_0$ value impacts clearly the tidal part of the velocity field while it barely affects the overdensity or divergent part of the velocity field. As $H_0$ gets larger, the infall onto the local Volume increases.

The second part of Table 2 summarizes the different values obtained for the reconstructions obtained with Tempel Grouping scheme and different $H_0$ values. Again, the same findings as with Tully Grouping are valid except that the standard deviations of both the velocity and overdensity fields are slightly higher, a first hint that structures are more contrasted in the WF reconstructions obtained with Tempel Grouping. Tempel Grouping reconstructions are also less affected by the infall or in other words for a given $H_0$ value, the monopole term is less negative in the reconstructions obtained with Tempel Grouping than with Tully Grouping. The dipole varies slightly more in Tempel grouping scheme’s case than in Tully grouping scheme’s case probably because of the higher number of constraints: at small radii the larger number of constraints generates more non linearities, at large radii the larger number of constraint slows the fields in their pace to reach the mean value. The two largest values of $H_0$ (75 and 76 km s$^{-1}$ Mpc$^{-1}$) present exceptions that deserve attention. A value of 75 km s$^{-1}$ Mpc$^{-1}$ results in a larger dipole value than the average at small radii while a value of 76 km s$^{-1}$ Mpc$^{-1}$ gives a field with a larger dipole value than the average at large radii. In addition, the monopole value at large radii for $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ is extremely high in absolute value. It clearly looks like there is a transition between values of 74 and 75 km s$^{-1}$ Mpc$^{-1}$ linked to the grouping scheme since none of these observations are valid for Tully Grouping scheme. This seems to imply that a more aggressive grouping has to be preferred for a better stability of the dipole and monopole of the velocity field whatever $H_0$ value is used.

Tests we made varying the default linking length (0.25 $h^{-1}$ Mpc at redshift zero changed to 0.20 or 0.30 $h^{-1}$ Mpc) in Tempel Grouping scheme and applying the WF technique to the resulting grouped catalogs show that indeed a large linking length permits increasing the stability but an excessive grouping (no more field galaxies) leads to wrong dipole values. This is in agreement with Sorce et al. 2013, that show that galaxies in the fields are an absolute necessity. Additionally $H_0$ has to be chosen with more care: minimizing in absolute value the mean of the velocity distribution seems a reasonable approach to choose the value of $H_0$. Again, we will temper this conclusion within the last part of this section.

The second third of Table 3 shows the properties of the residual between reconstructions obtained with Tempel Grouping scheme but different $H_0$ values. Overall, the same observations as with Tully Grouping scheme apply. One might notice that the residual values are larger than those obtained with Tully Grouping scheme. This is again due to the aggressiveness of the grouping. Indeed, in the tests made varying the default linking length, we observe that the variance between the two reconstructions obtained with different $H_0$ values is larger for the smallest linking length than for the default linking length used in the tests. Namely, grouping more eases slightly the dependence on $H_0$.

3.3 Comparisons between the grouping schemes

Figure 4 shows the residual between two WF reconstructions obtained with a different grouping scheme but with the same $H_0$ value. The figure is clear and irrevocable: while the velocity field is weakly affected by a different grouping scheme, the density field is largely impacted.
Note that the position of structures is not impacted, structures are reconstructed at the proper location in both grouping schemes but their density value varies. In other words the infall onto the large structures is slightly more important with Tempel Grouping scheme than with Tully Grouping scheme.

Actually, the last third of Table 2 gives the standard deviation of the residual velocity and overdensity fields of two reconstructions obtained with the exact same $H_0$ value but different grouping schemes. These values confirm that the velocity fields are quasi-identical except for the largest value of $H_0$ (76 km s$^{-1}$ Mpc$^{-1}$) but this value has been shown to be slightly unrealistic. This is in agreement with the fact that at larger $H_0$ values, Tully Grouping scheme produces overall a larger infall than Tempel Grouping scheme with the exception of $H_0=75$ km s$^{-1}$ Mpc$^{-1}$. Interestingly the standard deviation of the residual overdensity fields is not exceptionally high although Figure 3 clearly shows that the structures are affected by the grouping schemes. The answer is in the maximum value of the residual overdensity fields. The standard deviation might be quite low but the maximum value is clearly shows that the structures are affected by the grouping schemes.

Table 2. Properties of the reconstructed velocity and overdensity fields for different $H_0$ values and grouping schemes: (1) Grouping scheme, (2) Hubble constant, (3) standard deviation of the velocity field, (4) standard deviation of the overdensity field, (5) dipole value of the velocity field at 10 h$^{-1}$ Mpc, (6) dipole value of the velocity field at 240 h$^{-1}$ Mpc, the edge of the box/data, (7) monopole value of the velocity field at 240 h$^{-1}$ Mpc.

| Grouping Scheme | $H_0$ | $\sigma_v$ | $\sigma_\rho$ | Dipole at r=10 h$^{-1}$ Mpc | Dipole at r=240 h$^{-1}$ Mpc | Monopole at r=240 h$^{-1}$ Mpc |
|-----------------|------|----------|-------------|-----------------|-----------------|-----------------|
| Tully           | 72   | 320      | 0.20        | 477             | 144             | -83             |
|                 | 73   | 332      | 0.21        | 476             | 144             | -359            |
|                 | 74   | 369      | 0.21        | 478             | 144             | -634            |
|                 | 75   | 424      | 0.22        | 477             | 144             | -914            |
|                 | 76   | 491      | 0.23        | 479             | 144             | -1192           |
| Tempel          | 72   | 324      | 0.22        | 476             | 138             | -62             |
|                 | 73   | 339      | 0.22        | 445             | 138             | -264            |
|                 | 74   | 369      | 0.22        | 478             | 140             | -611            |
|                 | 75   | 615      | 0.23        | 624             | 140             | -1201           |
|                 | 76   | 495      | 0.24        | 420             | 183             | -797            |

Figure 1. Left: Supergalactic XY, YZ and XZ slices of the reconstructed velocity (arrow) and overdensity (contour) fields of the local Universe obtained with the catalog grouped with Tully scheme and $H_0=73$ km s$^{-1}$ Mpc$^{-1}$. The green color stands for the mean field. Dashed contours are underdense regions while solid contours are overdense areas. The reconstruction shows overall the local structures such as Shapley (top left in XY), Coma (top middle in XY and YZ) and Perseus Pisces (bottom right in XY). Right: as left panel but for the residual between reconstructions obtained with Tully grouping scheme and $H_0=72$ and 73 km s$^{-1}$ Mpc$^{-1}$ respectively. The residual highlights the impact of the Hubble constant value chosen to derive the distances and thus the peculiar velocity constraints. The larger $H_0$ is, the greater the infall onto the local Volume is.

To understand the difference emanating from the two grouping schemes in more detail, we look at the distribution of constraints in...
the XY supagalactic slice of the local Universe. Figure 2 shows the constraints as dots at galaxies’ position: a blue dot means a radial peculiar velocity pointing towards us while a red dot stands for a radial peculiar velocity going away from us. The dot sizes are proportional to the radial peculiar velocity value in absolute value. In a first approximation, i.e. on large scales, the distributions of constraints and their values look overall very similar. Next, we focus on particular regions of interest such as the Coma cluster area that has been shown to present values look overall very similar. In this last part, we investigate whether the WF reconstruction has a real strong dependence on the Hubble constant value. Indeed, in the above tests, the bias minimization scheme developed originally to suppress the infall observed in the reconstructions has not been applied to the observational catalog. However, to build adequate constrained initial conditions, the observational catalog must undergo a bias minimization. We apply the method described in Sorce (2015) to the different H₀ values catalogs grouped with Tempel scheme and run the WF technique on each one of them. Results are visible on Figure 2 in form of the monopole of the velocity fields. The bias minimization scheme strongly reduces the effect of the H₀ value selected to derive the peculiar velocities. There is clearly no strong infall anymore onto the local volume (no large negative values for the monopole at large radii) whatever H₀ value is used. This observation drastically minimizes the previous conclusions about the dependence of the reconstruction on H₀ and removes concerns about choosing adequately H₀ providing that the catalog is bias minimized.

### 3.4 H₀: Not a real dependence

In this last part, we investigate whether the WF reconstruction has a real strong dependence on the Hubble constant value. Indeed, in the above tests, the bias minimization scheme developed originally to suppress the infall observed in the reconstructions has not been applied to the observational catalog. However, to build adequate constrained initial conditions, the observational catalog must undergo a bias minimization. We apply the method described in Sorce (2015) to the different H₀ values catalogs grouped with Tempel scheme and run the WF technique on each one of them. Results are visible on Figure 2 in form of the monopole of the velocity fields. The bias minimization scheme strongly reduces the effect of the H₀ value selected to derive the peculiar velocities. There is clearly no strong infall anymore onto the local volume (no large negative values for the monopole at large radii) whatever H₀ value is used. This observation drastically minimizes the previous conclusions about the dependence of the reconstruction on H₀ and removes concerns about choosing adequately H₀ providing that the catalog is bias minimized.

### Table 3. Properties of the residual between reconstructed velocity and overdensity fields obtained with different H₀ values and different grouping schemes:

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Grouping Scheme 1-2 | H₀ | σₓ | σᵧ | ρₚmax |
| Tempel - Tempel | 3.4 H₀ Mpc⁻¹ | 1-10 km s⁻¹ | km s⁻¹ | |
| 72 - 73 | 95 | 0.03 | 1.0 |
| 72 - 74 | 187 | 0.06 | 1.4 |
| 72 - 75 | 282 | 0.1 | 1.5 |
| 72 - 76 | 375 | 0.13 | 2.1 |
| Tully - Tully | 72 - 73 | 93 | 0.03 | 0.9 |
| 72 - 75 | 187 | 0.06 | 1.2 |
| 72 - 76 | 94 | 0.03 | 0.9 |
| 74 - 76 | 187 | 0.06 | 1.3 |
| 75 - 76 | 93 | 0.03 | 1.3 |
| Tempel - Tempel | 72 - 73 | 128 | 0.03 | 1.0 |
| 72 - 74 | 187 | 0.06 | 1.4 |
| 72 - 75 | 448 | 0.1 | 2.0 |
| 72 - 76 | 427 | 0.1 | 2.4 |
| Tully - Tully | 73 - 73 | 147 | 0.03 | 0.8 |
| 73 - 75 | 401 | 0.06 | 1.3 |
| 73 - 76 | 383 | 0.1 | 1.8 |
| 74 - 75 | 298 | 0.03 | 0.9 |
| 74 - 76 | 366 | 0.06 | 1.1 |
| 75 - 76 | 519 | 0.03 | 0.8 |
| Tempel - Tempel | 72 - 72 | 43 | 0.07 | 4.0 |
| 72 - 73 | 117 | 0.07 | 4.1 |
| 72 - 74 | 43 | 0.07 | 4.3 |
| 72 - 75 | 254 | 0.07 | 4.2 |
| 73 - 76 | 400 | 0.07 | 4.7 |

- Table 3. Properties of the residual between reconstructed velocity and overdensity fields obtained with different H₀ values and different grouping schemes:

  - (1) Grouping scheme of the reconstruction number 1
  - (2) H₀ value used for the first reconstructed field
  - (3) H₀ value used for the second reconstructed field
  - (4) Standard deviation of the residual velocity field
  - (5) Maximum of the residual overdensity field

the importance of a balance between grouping and removing non linear motions.
Grouping

Figure 3. As Figure 1 but obtained with Tempel grouping scheme.

Figure 4. Supergalactic XY, YZ and XZ slices of the residual between reconstructed velocity (arrow) and overdensity (contour) fields of the local Universe obtained with the catalog grouped with Tempel and Tully schemes. The green color stand for the null value. The residual shows that overall the local structures such as Coma (top middle in XY and ZY) are more pronounced in the reconstruction obtained with Tempel grouping scheme than in that obtained with Tully grouping scheme.

4 CONCLUSION

Reconstructions of the three dimensional velocity and density fields of the local Universe are essential to study the local Large Scale Structure. Numerous methodologies have been developed to perform such reconstructions using observational data. In this paper, we use the Wiener Filter technique applied to galaxy radial peculiar velocity catalogs to obtain reconstructed velocity and overdensity fields of the local Volume. These reconstructions are useful as such for direct study of the linear local Universe today but also to build constrained initial conditions that permit performing constrained simulations of the local Universe, i.e. simulations that resemble the local Universe down to the cluster scales. We seek to understand how the Hubble constant value chosen to derive the radial peculiar velocities from galaxy distance measurements and total velocities, and the grouping scheme used to remove non linear motions affect the reconstructions and by extension impact the quality of the constrained simulations.

To this end, two different grouping schemes (Tully based on the literature and Tempel based on a systematic algorithm) are selected as well as 5 reasonable locally derived \( H_0 \) values (from 72 to 76 km s\(^{-1}\) Mpc\(^{-1}\), for the most recent values see e.g. Singh et al. 2016, Riess et al. 2016, Tully et al. 2016, Beaton et al. 2016). 10 grouped versions of the second radial peculiar velocity catalog of Cosmicflows are produced accordingly: 5 per grouping scheme with each one of the \( H_0 \) values. These catalogs differ by the number of isolated galaxies and groups as well as by their radial peculiar velocity distribution. Tempel Grouping scheme results in more isolated galaxies but less groups and as a result less peculiar velocity-constraints when compared to Tully Grouping scheme. Namely, the latter is found to be more aggressive than the former. In addition, the larger \( H_0 \), the more asymmetric the distribution, the larger the standard deviation and the more negative the mean.

The WF algorithm is applied to these 10 catalogs and the resulting velocity and overdensity fields are compared. Whatever grouping scheme is used, the larger \( H_0 \) is, the larger the inflow onto the local Volume is. If the tidal part of the velocity field due to objects outside of the local Volume is greatly affected by \( H_0 \), the divergent part due to the objects inside the Volume and tightly tied to the overdensity field is weakly impacted by a change in \( H_0 \). Note that it is the latter that is used to build constrained initial conditions. Actually, the latter is greatly affected by the grouping scheme. Comparing at fixed \( H_0 \), reconstructions obtained with catalogs grouped with different grouping...
The main conclusions of the paper are as follows. The choice of $H_0$ impacts overall the velocity field in a given direction, i.e. it creates a general infall/outflow patterns but it does not really affect the overdensity field. Namely, the tidal part of the velocity field changes quite a lot with $H_0$ but not the divergent part. However, this conclusion has to be strongly mitigated. Indeed, the bias minimization scheme described in Sorce (2013) applied to the grouped observational catalog strongly suppresses the dependence of the reconstructions on $H_0$. There is no more drastic infall onto the local volume. On the contrary, the grouping scheme affects greatly the overdensity field accentuating or diminishing the contrast between the structures. Still overall structures are reconstructed at the proper location with both grouping schemes studied here. Then in terms of $H_0$, we simply recommend either to choose the value giving the more neutral result (i.e. monopole term close to zero at large radii) or to apply the bias minimization scheme described in Sorce (2013) after grouping. Note that this bias minimization scheme, we observe that structures, although they are present at the proper location in both cases, are more contrasted in Tempel grouping scheme’s case then in Tully grouping scheme’s case. This is in particular true for the Coma cluster area and the Centaurus cluster region. Looking for the reasons of such observations, we compare the distribution of radial peculiar velocity in the XY supergalactic slice and notice that overall the agreement between the catalogs grouped with the two different schemes is very good: positions of constraints (peculiar velocities) and their values match quite closely. However, when focusing on smaller areas to study the details, like the Coma cluster region or the Centaurus cluster region, we note quite a lot of differences mostly due to the difference in terms of aggressiveness of the grouping schemes. Tempel Grouping scheme allows more constraints in these regions than Tully Grouping scheme. Consequently the infall from both sides onto these areas are reinforced providing an explanation for the greater overdensity value in the reconstruction obtained with the Tempel grouped catalog than in that obtained with the Tully grouped catalog. Such findings highlight the importance of a balance between grouping to remove non linear motions and preserving some constraints to produce an infall onto structures that are expected to be large overdensities.

**Figure 5.** XY supergalactic slice ($10 \ h^{-1} \text{Mpc}$) of the local Universe showing the constraints (radial peculiar velocity at galaxies’ position) obtained with Tully (top) and Tempel (bottom) grouping schemes. A red dot means that the radial peculiar velocity is positive while a blue dot means that it is negative. The dot size is proportional to the absolute value of the radial peculiar velocity. Overall, the two grouping scheme exhibits catalogs in agreement with each other, the constraints are quite similar. However, zooming on a particularly dense region, like the Coma cluster area or the Centaurus cluster region, differences are more pronounced. Tempel grouping scheme presents more constraints with large values reinforcing the infall onto Coma/Centaurus (from both sides) that explains the contrast between Coma/Centaurus areas reconstructed using the second catalog of Cosmicflows obtained with the two different grouping schemes.

**Figure 6.** Monopole of the Wiener Filter reconstructed fields as a function of the distance from us. The Wiener Filter has been applied to catalogs with different $H_0$ values (linestyle) using a unique grouping scheme but applying (blue) or not (red) a method to minimize the observational biases. $H_0$ impacts strongly the monopole term only for the catalogs without minimization of biases. The larger $H_0$, the larger is the infall on the local Volume. The minimization bias scheme has a strong influence on the monopole of the velocity field: it clearly suppresses the infall for all the values of $H_0$ considered.
tion scheme also erases the bump entirely due to biases in the dipole term and makes the radial peculiar velocity distribution Gaussian. It is worth noticing that again, the dipole at large radii is proven to be very stable whatever choices is made to build the WF reconstruction providing that the grouping is properly done and that the catalog contains both clusters/groups and galaxies in the field (e.g. Sorce et al. 2017). Regarding the grouping scheme, there is a clear need for a balance between grouping to remove non linear motions to preserve the quality of both clusters and galaxies in the field (e.g. Sorce et al. 2017).

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APPENDIX A

The Wiener Filter technique is the optimal minimal variance estimator given a dataset and an assumed prior power spectrum. Data dominate the reconstruction in region where they are dense and accurate. On the opposite when they are noisy and sparse, the reconstruction is a prediction based on the assumed prior model. Briefly, the overdensity $\delta_{WF}$ and velocity $v_{WF}$ fields of the Wiener Filter are expressed in terms of the following correlation matrixes. For a list of $M$ constraints $c_i$:

$$\delta_{WF}(r) = \sum_{i=1}^{M} \langle \delta(r)c_i \rangle \eta_i, \quad (4)$$

$$v_{WF} = \sum_{i=1}^{M} \langle v(r)c_i \rangle \eta_i \quad \text{with} \; \alpha = x, y, z. \quad (5)$$

where $\eta_i = \sum_{j=1}^{M} (C_i C_j^{-1}) c_j$ are the components of the correlation vector $\eta_i$. $C_i = c_i + \tilde{c}_i$ are observational constraints plus their uncertainties. Hence, $(C_i C_j^{-1})$ is equal to $(c_i c_j) + \tilde{c}_i \delta_j$ assuming statistically independent errors. The constraints can be either densities or velocities. $\langle AB \rangle$ notations stand for the correlation functions involving the assumed prior power spectrum.

The associated correlation functions are given by:

$$\langle \delta(r') \delta(r+r') \rangle = \frac{\hat{d}_f}{(2\pi)^3} \int \frac{d^3k}{k^3} P(k)e^{i k \cdot (r'-r)} \; dk$$

$$= \hat{d}_f \Gamma \langle \delta \rangle \; \quad (6)$$

$$\langle v_x(r') v_y(r+r') \rangle = \frac{\hat{d}_f}{(2\pi)^3} \int \frac{d^3k}{k^3} \frac{k_y k_z}{k^2} P(k)e^{i k \cdot (r'-r)} \; dk$$

$$= \hat{d}_f \langle \delta \rangle \Psi_{xy} \; \quad (7)$$

where $P$ is the assumed prior power spectrum, $\alpha$ the scale factor and $f$ the growth rate.

Because data sample a typical realization of the prior model, i.e. the power spectrum, $\chi^2_{data}$ should be close to 1 where $\chi^2 = \sum_{i=1}^{M} \sum_{j=1}^{M} C_i (C_i C_j^{-1}) C_j$ and $d.o.f.\; \text{is the degree of freedom. However, data include non-linearities which are not taken into account in the model. Consequently, a non linear sigma (\sigma_{NL}) such that } \langle C_i C_j \rangle = \langle c_i c_j \rangle + \delta_i \delta_j + f^2 P_{NL}$ is required to compensate for the non-linearities to drive $\frac{\chi^2_{data}}{d.o.f.}$ closer to 1.

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