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KINEMATIC DISTANCES OF GALAXIES IN THE LOCAL VOLUME

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We consider the kinematic distances to nearby galaxies obtained by the Numerical Action Method (NAM) based on the Cosmic-flow-3 survey data. NAM-distances are compared with 418 high-precision distances measured by the Tip of the Red Giant Branch (TRGB) method using the Hubble Space Telescope. We estimated the average difference $< D_{NAM} - D_{TRGB} > = -0.30 \pm 0.08$ Mpc and the standard deviation of 1.57 Mpc. Approximately the same difference in the distance scale is obtained in comparison with less accurate distance estimates through the membership of galaxies in known groups or from the Tully-Fisher relation. We conclude that the NAM method provides distance estimates with an accuracy of 20% within the Local Volume, which is valid for ~90% of the sky, except for the regions of the Virgo cluster and the Coma-I group.

Keywords: *galaxies: kinematic distances: Local Volume*

1. *Introduction*. Constructing a representative sample of nearby galaxies, limited by a fixed volume, is a necessary observational basis for cosmology on small scales. Efforts to create such a sample have been made repeatedly [1,2]. Currently, the catalog of candidates for the population of the Local Volume (LV) contains about 1500 galaxies with expected distances D within 11 Mpc [3]. The on-line version of this Local Volume galaxy data base (LVGDB) [4], supplemented by recently discovered objects, is available at http://www.sao.ru/lv/lvgdb.

With an ideal unperturbed Hubble flow with a Hubble parameter $H_0 = 73$ km s^{-1} Mpc^{-1}, galaxies with radial velocities relative to the centroid of the Local Group $V_{LG} < 800$ km s^{-1} would fall into the designated LV. The presence of inhomogeneities in the distribution of matter introduces anisotropy into the local Hubble flow. According to [5], our Galaxy and its neighbors are participating in the motion towards the nearby Virgo cluster ($D = 16.5$ Mpc) with an amplitude of ~180 km s^{-1} and in the expansion of the Local Void with a characteristic velocity of ~260 km s^{-1}. The directions of these local flows are approximately mutually perpendicular.

To construct a more detailed map of the local field of radial velocities, the Numerical Action Method (NAM) [6,7] was proposed, which takes into account the location and masses of nearby attractors (groups of galaxies), as well as the most significant neighboring clusters and voids outside the L.V.Kourkchi et al. [8] developed a convenient scheme for determining the kinematic NAM-distances of LV galaxies from their coordinates and radial velocity V_g relative to the center of our Galaxy. In this case, estimates of the distance of galaxies made by various methods were used. The main array consisted of high-precision measurements of distances by the luminosity of the Tip of the Red Giant Branch (TRGB) with a total number of about 400. The accuracy of this method reaches ~5%. Actually, the radius of the LV, 11 Mpc, was determined just by the ability to measure the TRGB-distance of a galaxy from its images obtained with the Hubble Space Telescope (HST) during one orbital period. In addition to this universal method, applicable to galaxies of any morphological type, a small number of distance estimates were used from Cepheids, supernovae, and surface brightness fluctuations.

It should be noted that measuring the distances of galaxies with an accuracy of ~5% is a laborious, expensive procedure, unlike measuring radial velocities. Mass surveys of radial velocities in the optical and radio ranges [9-12] have significantly enriched our data on the field of radial velocities of galaxies in the LV. This growth continues with the introduction of ever larger telescopes into observations. On the other hand, episodic programs for measuring TRGB-distances on the aging HST make an increasingly smaller contribution to the overall panorama of galaxy distances beyond $D \sim 3$ Mpc. Therefore, estimates of kinematic NAM-distances, which allow us to determine the absolute luminosity and other important parameters of nearby galaxies, are becoming more relevant.

The purpose of this work is to estimate the accuracy of kinematic distances of galaxies in the Local Volume, using observational data from the LVGDB.

2. *Observational data*. The LVGDB contains TRGB-distance values for 473 LV galaxies with measured radial velocities. We excluded from them 43 members of the Local Group with distances $D < 1$ Mpc, whose virial motions are not related to the general pattern of the peculiar velocity field of the LV. For the remaining 430 galaxies, kinematic NAM-distances were determined according to the diagram [8]. For most of these galaxies, their radial velocities are measured with an error of less than 8 km s^{-1}, corresponding to an error in D_{NAM} of less than 0.1 Mpc, which we neglected. A machine-readable list of these galaxies with D_{TRGB} and D_{NAM} values can be provided upon individual request.

3. *The local kinematic distances*. The top panel of Fig.1 reproduces the distribution of 430 LV galaxies according to the difference in distance estimates $\Delta = D_{NAM} - D_{TRGB}$ in equatorial coordinates. The color scale on the right reflects the magnitude of Δ in Mpc. Over the predominant area of the sky, galaxies, denoted by circles, have a yellow-green color, corresponding to the difference in distance estimates within 1 - 2 Mpc. The left side of the sky map is characterized

by a vast emptiness, due to the fact that the Local Void extends almost to the border of the Local Group of galaxies.

The bottom panel of Fig.1 shows the distribution on the sky of LV galaxies according to the magnitude of the distance ratio D_{NAM}/D_{TRGB} in the same coordinates. This diagram complements the previous one, since the error $\sigma(D_{TRGB}) \sim 5\%$ affects the value of $(D_{NAM} - D_{TRGB})$ differently for nearby and distant galaxies. Typical

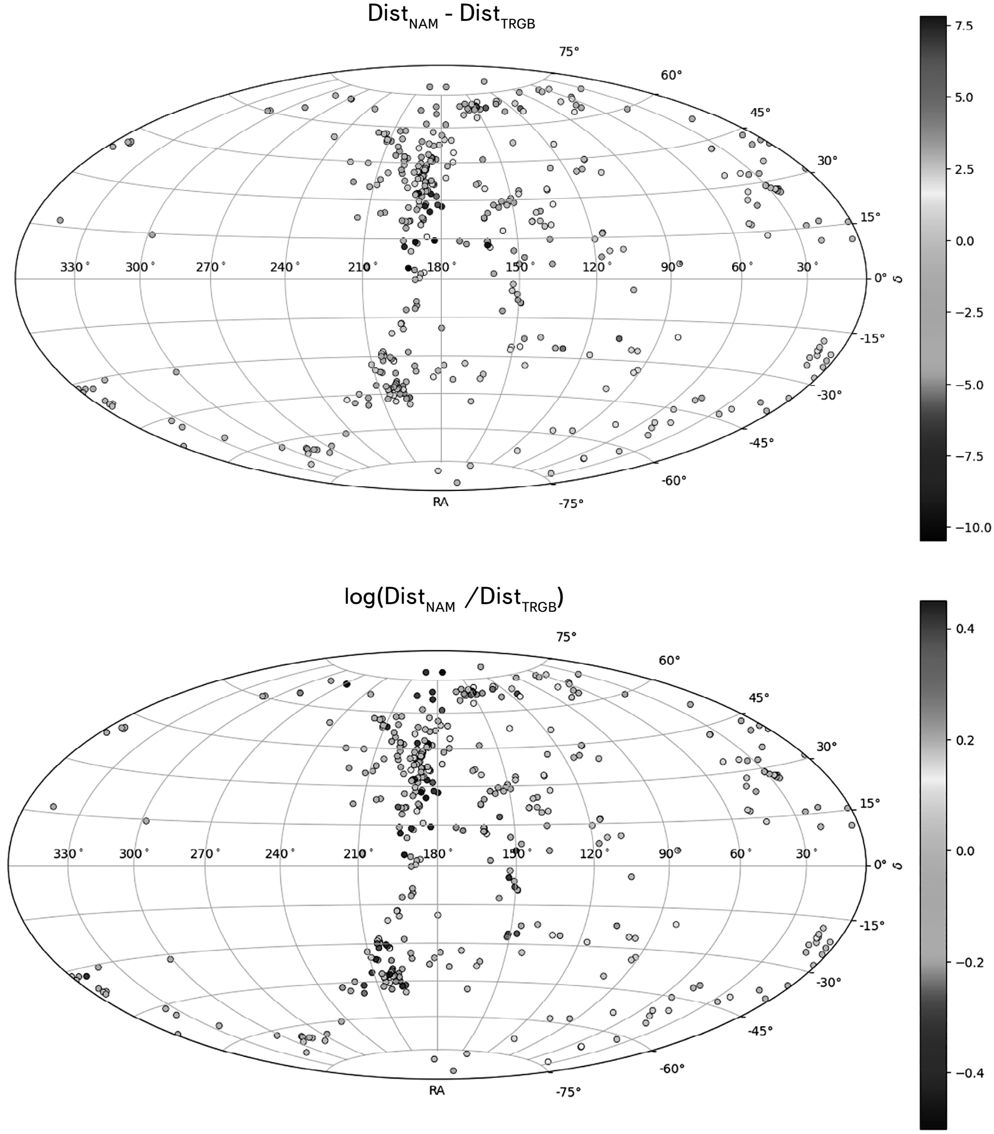

Fig.1. Distribution of galaxies in the Local Volume by the difference (top) and ratio (bottom) of the distances D_{NAM} and D_{TRGB}.

virial velocities in groups, $\sigma_v \sim (70-100)$ km s^{-1}, are also the reason for the scatter of galaxies in terms of the value of D_{NAM}/D_{TRGB}, especially in nearby groups around M81 and CenA = NGC5128.

The distribution of the number of LV galaxies according to the magnitude of the difference in distance estimates $\Delta = D_{NAM} - D_{TRGB}$ is shown in Fig.2. We excluded 12 strongly deviating galaxies with $|\Delta| > 5.0$, their relative number does not exceed 3%. The histogram $N(\Delta)$ fits well with the Gaussian function having parameters $\langle\Delta\rangle = -0.3 \pm 0.08$ Mpc and $\sigma_\Delta = 1.57$ Mpc.

Table 1 presents a list of 12 "outlier" galaxies with $|\Delta| > 5$ Mpc. Its first column lists the names of galaxies as they are designated in LVGB; columns (2, 3) give the equatorial coordinates of the galaxies; column (4) contains radial velocities relative to the center of the Galaxy; the distances of galaxies and their difference in Mpc are given in the last three columns. Analysis of these data reveals several reasons for the large deviations Δ. For the galaxy UGC4998, an erroneous determination of the D_{TRGB} distance was made on the "color-magnitude" diagram [13] due to confusion between the *RGB* and *AGB* sequence stars. The galaxies IC3023, KDG177, UGC7983, and UGC8061 are located inside the virial zone of the Virgo cluster, where NAM-distance estimates are distorted by virial motions. The galaxies BTS76, LVJ1205+28, LVJ1207+31, LVJ1217+32, AGC229053, and IC3341 belong to members of the specific Coma I group, around NGC4278 [14], which is located at the border of the zero-velocity radius of the Virgo cluster, $R_0 \simeq 23^\circ$. The galaxies of this group have negative peculiar velocities $V_{pec} \sim -800$ km s^{-1}. The nature of this anomaly remains a mystery.

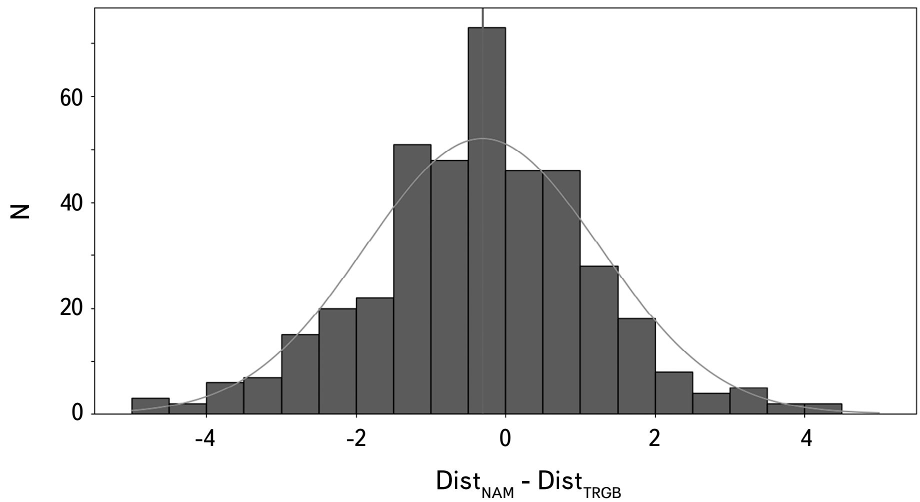

Fig.2. Distribution of number of galaxies in the Local Volume by the magnitude of difference in their distance estimates $\Delta = D_{NAM} - D_{TRGB}$.

Table 1

A LIST OF 12 "TRGB - NAM" OUTLIERS

Name	RA deg	Dec deg	V_g km s^{-1}	D_{TRGB} Mpc	D_{NAM} Mpc	Δ_D Mpc
UGC04998	141.30	68.38	742	8.24	13.69	5.45
NGC3379	161.96	12.58	818	11.32	19.13	7.81
BTS76	179.68	27.58	436	12.59	5.17	-7.42
LV J1205+28	181.39	28.23	491	11.53	5.65	-5.88
LV J1207+31	181.96	31.55	559	12.02	6.64	-5.38
IC3023	182.51	14.37	755	17.0	6.73	-10.27
LV J1217+32	184.38	32.53	456	12.59	5.32	-7.27
AGC229053	184.56	25.57	409	12.47	4.45	-8.02
IC3341	186.60	27.75	368	11.64	3.94	-7.70
KDG177	189.99	13.78	958	17.0	7.74	-9.26
UGC07983	192.45	03.84	619	16.52	6.06	-10.46
UGC08061	194.18	11.93	520	12.59	5.21	-7.38

At an average distance of LV galaxies of 8.0 Mpc and a standard deviation $\sigma_\Delta = 1.57$ Mpc, the relative error in estimating the NAM-distance is 19%. Here we made a quadratic subtraction of the relative error of 5% caused by errors in measuring TRGB distances.

For dwarf galaxies in the Local Volume groups, virial velocities of ~80 km s^{-1} introduce a relative error in the NAM-distance estimate of about 12%. Therefore, when using the average radial velocity in a sufficiently populated group, one can expect a typical error in the average NAM-distance of ~15%.

To test this assumption, we listed in Table 2 all 22 major LV galaxies with

Table 2

THE MAJOR LOCAL VOLUME GALAXIES

Name	D_{TRGB}	D_{NAM}	Δ_D	Name	D_{TRGB}	D_{NAM}	Δ_D
NGC 253	3.70	3.83	0.13	NGC4594	9.55	8.71	-0.84
NGC 628	10.19	9.58	-0.61	NGC4736	4.41	4.03	-0.38
NGC 891	9.95	10.39	0.44	NGC5055	9.04	7.18	-1.86
NGC1291	9.08	9.16	0.08	NGC5128	3.68	3.46	-0.22
IC 342	3.28	3.70	0.42	M 51	8.40	7.13	-1.27
NGC2683	9.82	10.51	0.69	NGC5236	4.90	2.97	-1.93
NGC2903	9.15	10.86	1.71	M 101	6.95	4.85	-2.10
M 81	3.70	1.84	-1.86	NGC6744	9.51	8.63	-0.88
NGC3115	9.68	10.39	0.71	NGC6946	7.73	5.41	-2.32
NGC3184	11.12	11.42	0.30	NGC3379	11.32	19.13	7.81
NGC4258	7.66	7.33	-0.33	NGC3627	11.12	6.72	-4.40

the Milky Way - like luminosity and accurate distance estimates. These galaxies dominate in mass in their groups, and it can be expected that their peculiar velocities are small. As follows from these data, the average difference in distance estimates for them is $\langle D_{NAM} - D_{TRGB} \rangle = -0.51 \pm 0.27$ Mpc, and the relative standard deviation of the difference is 15%. Note that the following galaxies were added to the 16 galaxies in the table with TRGB distances: IC342 with a distance estimate from Cepheids, NGC3115 with a distance estimate from surface brightness fluctuations, and NGC3184, M51, whose distances are determined by the luminosity of supernovae. The bottom two lines of Table 2 show the galaxies NGC3379 and NGC3627, which are massive but not dominant in their groups in the Leo Spur region [15]. According to [7], this region has a complex structure of the peculiar velocity field due to the projection onto the line of sight of two structures: the Leo Spur and the Leo cloud [16] and the presence of a void behind the Leo cloud.

4. *Comparison with other distance estimates*. The LVGDB database contains 94 galaxies with measured radial velocities, whose distances are estimated by the assumed membership (mem) in nearby groups. Of these, we excluded 9 galaxies with deviations $|D_{NAM} - D_{mem}| > 5.0$ Mpc. They are located in the Leo I (NGC3379) and Sombrero (NGC4594) groups with large virial velocities. For the remaining 85 galaxies, we obtained the values $\langle D_{NAM} - D_{mem} \rangle = -0.23$ Mpc and $\sigma_{\Delta} = 1.97$ Mpc. The relative error of the difference Δ for them is 21%. Assuming that the relative error of NAM distances is 15%, we find approximately the same value for the error of mem-distances, 15%.

The LVGDB database also contains 159 galaxies with distance estimates based on the Tully-Fisher method [17], using the relationship between the luminosity of a galaxy and the width of the 21-cm HI line. We excluded from consideration 16 galaxies with a large difference $|D_{NAM} - D_{TF}| > 16$ Mpc, which make up 10% of this sample. All of them, except for one, are located inside the virial zone of the Virgo cluster ($n = 9$) or the Coma I group ($n = 6$) with anomalous peculiar velocities. Among these excluded objects, the galaxy UGC7774 (RA = 189°.03, Dec = +40°.00) has estimates $D_{TF} = 22.6$ Mpc and $D_{NAM} = 7.2$ Mpc, but is not in any known group. For the remaining 143 galaxies, we obtained the values $\langle D_{NAM} - D_{TF} \rangle = -0.76 \pm 0.35$ Mpc and $\sigma(D_{NAM} - D_{TF}) = 4.19$ Mpc. Given the average distance of the galaxies in this sample, $\langle D_{TF} \rangle = 11.1$ Mpc, we obtain a relative error in the TF distance estimate of 31%. This value is noticeably larger than the typical error of the TF method, 20%, obtained for spiral galaxies. This difference is quite understandable, since dwarf galaxies dominate in the LV, and their irregular shape makes the correction for the inclination of their axis of rotation to the line of sight uncertain.

5. *Concluding remark.* A comparison of kinematic distance estimates made in the NAM model with distance measurements using the TRGB method and other methods shows a small but systematic shift in the NAM scale, $\langle D_{NAM} - D_{TRGB} \rangle = -0.30 \pm 0.08$ Mpc. The relative error in determining the kinematic distance is ~20% for individual galaxies in the Local Volume. If there are several members in the group with measured radial velocities, the error of the NAM method can be improved to 15%. This makes the NAM method more preferable compared to the Tully-Fisher method, the relative error of which for the LV population we estimated as 31%.

However, there are two adjacent areas in the sky: the zone of galaxies falling onto the Virgo cluster with a radius of ~23° and the zone of large negative peculiar velocities in the Coma I group north of the Virgo cluster, where the kinematic method gives large errors and is practically inapplicable. The total area of these anomalous regions occupies only 10% of the sky. Taking into account this caveat, the kinematic method in the NAM model is quite suitable for the mass determination of distances for nearby galaxies with an error of 15-20%.

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КИНЕМАТИЧЕСКИЕ РАССТОЯНИЯ ГАЛАКТИК В МЕСТНОМ ОБЪЕМЕ

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Рассмотрены кинематические расстояния до близких галактик, полученные методом численного действия (NAM), основанным на данных обзора Cosmicflow-3. Расстояния NAM сравниваются с 418 высокоточными расстояниями, измеренными методом вершины ветви красных гигантов (TRGB) с помощью космического телескопа Хаббла. Мы оценили среднюю разницу $< D_{NAM} - D_{TRGB} > = -0.30 \pm 0.08$ Мпк и стандартный разброс в 1.57 Мпк. Примерно такая же разница в масштабе расстояний получается по сравнению с менее точными оценками расстояний через принадлежность галактик к известным группам или из соотношения Талли-Фишера. Мы пришли к выводу, что NAM-метод дает оценки расстояний с погрешностью 20% в пределах Местного объема, что справедливо для ~90% неба, за исключением областей скопления Virgo и группы Coma-I.

Ключевые слова: *галактики: кинематические расстояния: Местный объем*

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