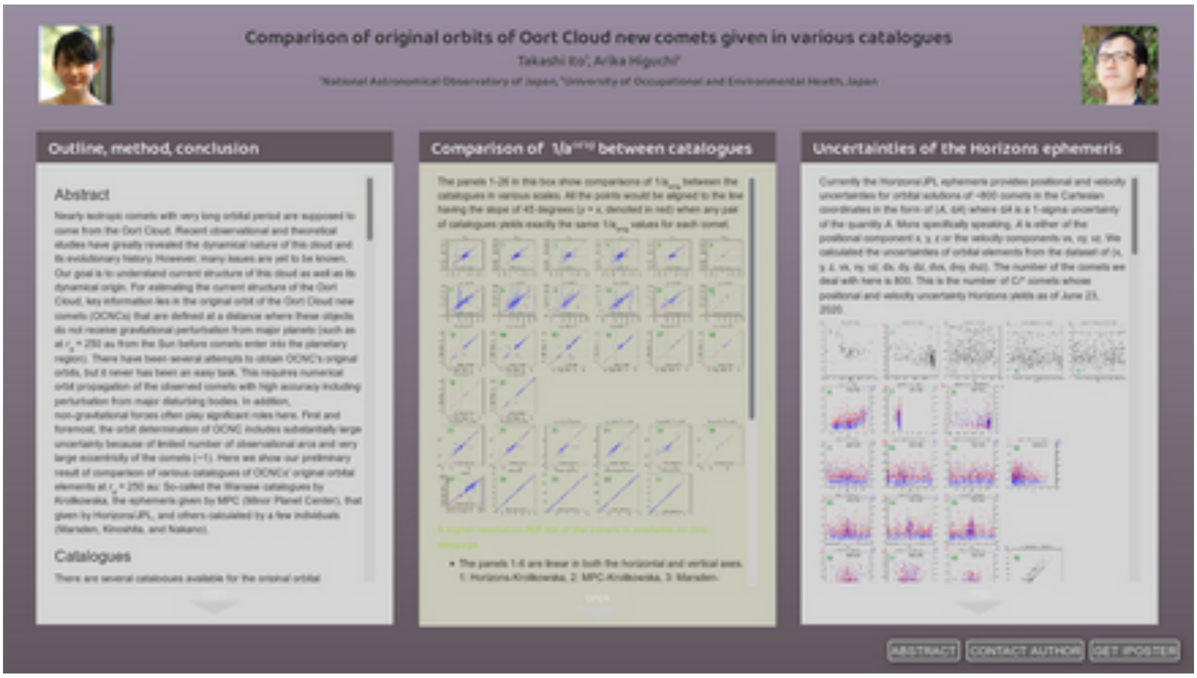
# Comparison of original orbits of Oort Cloud new comets given in various catalogues

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# OUTLINE, METHOD, CONCLUSION

## Abstract

Nearly isotropic comets with very long orbital period are supposed to come from the Oort Cloud. Recent observational and theoretical studies have greatly revealed the dynamical nature of this cloud and its evolutionary history. However, many issues are yet to be known. Our goal is to understand current structure of this cloud as well as its dynamical origin. For estimating the current structure of the Oort Cloud, key information lies in the original orbit of the Oort Cloud new comets (OCNCs) that are defined at a distance where these objects do not receive gravitational perturbation from major planets (such as at $r_g$ = 250 au from the Sun before comets enter into the planetary region). There have been several attempts to obtain OCNC's original orbits, but it never has been an easy task. This requires numerical orbit propagation of the observed comets with high accuracy including perturbation from major disturbing bodies. In addition, non-gravitational forces often play significant roles here. First and foremost, the orbit determination of OCNC includes substantially large uncertainty because of limited number of observational arcs and very large eccentricity of the comets (~1). Here we show our preliminary result of comparison of various catalogues of OCNCs' original orbital elements at $r_g$ = 250 au: So-called the Warsaw catalogues by Krolikowska, the ephemeris given by MPC (Minor Planet Center), that given by Horizons/JPL, and others calculated by a few individuals (Marsden, Kinoshita, and Nakano).

## Catalogues

There are several catalogues available for the original orbital elements of the Oort Cloud comets (see *Abstract* for the definition of the original orbit). What we use and compare in this study are as follows:

- Malgorzata Krolikowska's series of catalogues. Recently the whole dataset was summarized on an website (https://pad2.astro.amu.edu.pl/comets/). As for the details of the theoretical background and implementation of the calculations, see the series of her publications: Krolikowska (2014) (https://ui.adsabs.harvard.edu /abs/2014A%26A...567A.126K/abstract), Krolikowska+ (2014) (https://ui.adsabs.harvard.edu /abs/2014A%26A...571A..63K/abstract), Krolikowska and Dybczynski (2017) (https://ui.adsabs.harvard.edu /abs/2017MNRAS.472.4634K/abstract), Krolikowska and Dybczynski (2018) (https://ui.adsabs.harvard.edu /abs/2019MNRAS.484.3463K/abstract), Krolikowska (2020) (https://ui.adsabs.harvard.edu /abs/2020A%26A...633A..80K/abstract), Krolikowska and Dybczynski (2020) (https://arxiv.org/abs/2005.09698) On the website (https://pad2.astro.amu.edu.pl/comets/), the original orbits of 277 comets (together with their previous, current, next, and future orbits) are available with orbital uncertainties. The series of her catalogues have been widely known and accepted as the most reliable ones. Note that some of the cometary orbits in these catalogues are determined with non-gravitational effect, but we do not discuss this point in this poster.
- The online ephemeris that Horizons/JPL provides. We can specify objects names and epoch, and obtain estimate of cometary orbits at an arbitrary time between 1600 AD to 2200 AD (this period is longer for some comets). This ephemeris includes orbital information of 2899 C/* comet as of June 23, 2020. Add to that, recently this ephemeris began yielding position and velocity uncertainties for orbital solutions for some comets in the form of (x, y, z, vx, vy, vz, dx, dy, dz, dvx, dvy, dvz) where dA is a 1-sigma uncertainty of the quantity A. See https://ssd.jpl.nasa.gov/horizons.cgi (https://pad2.astro.amu.edu.pl/comets/) for more detail.
- The online ephemeris that MPC (Minor Planet Center) provides. This ephemeris includes 2799 C/* comets, and some of them are given their original semimajor axis ($1/a_{orig}$) but without uncertainties. See https://minorplanetcenter.net/ (https://pad2.astro.amu.edu.pl/comets/) for more detail.
- The online comet catalogue that Brian Marsden published in 2004. This is a list of the Oort Cloud cometary orbits mostly focused on their original values. $1/a_{orig}$ of 426 comets is provided without uncertainties. There is no online version for this catalogue.
- Another version of Brian Marsden's cometary catalogue that Marc Fouchard provided us through Julio Fernandez in 2018. $1/a_{orig}$ of 738 comets is provided without uncertainties. There is no online version of this catalogue.
- An online comet catalogue that Shuiti Nakano provides (named the "Nakano Note"). This ephemeris includes the original semimajor axis ($1/a_{orig}$) of some comets. This catalogue includes 439 C/* comets, some of them having $1/a_{orig}$ without uncertainties. See http://www.oaa.gr.jp/~oaacs/nk.htm (http://www.oaa.gr.jp/~oaacs/nk.htm) for more detail.
- An online comet catalogue that Kazuo Kinoshita provides. This ephemeris includes original semimajor axis ($1/a_{orig}$) of some comets. This catalogue includes 105 C/* and A/* comets, some of them having $1/a_{orig}$ without uncertainties. See https://jcometobs.web.fc2.com/ (https://jcometobs.web.fc2.com/)for more detail.

## Comparison of $1/a_{orig}$

The panels in the central box in this poster show some comparison results of $1/a_{orig}$ between the various catalogues. Here are some general remarks and comments:

- All the points would be aligned with the line having the slope of 45 degrees ($y = x$) if any pair of catalogues yields exactly the same $1/a_{orig}$ values for each comet.
- In some panels, data points have uncertainties in the vertical direction that Krolikowska's catalogue gives.
- In this study we particularly pay attention to the comparison between Krolikowska's catalogue and Horizons' ephemeris. The majority of the community presumes that Krolikowska's catalogue is the most accurate and reliable. However, the number of samples is small. Horizons' ephemeris provides with the largest number of comet samples.
- First, take a look at the panel 1 in the central box and its magnified version, the panel 7. Although we see some scatter of the points that indicates the difference of estimates of $a_{orig}$ between the two catalogues, we should overall say that most of the dots are concentrated on the $y = x$ line within the given uncertainties. We do not see any systematic trends on the plots except for very few exceptions of the hyperbolic comets ($1/a_{orig} < 0$) that Horizons yields. This characteristic is also apparent in a magnified panel, 21.
- The above fact is also the case in the comparisons between Krolikowska's catalogue and MPC's ephemeris, Marsden's catalogue, and Fernandez's (Fouchard's) catalogue.
- We see some systematic differences of $1/a_{orig}$ between the values given by Krolikowska and by Nakano as well as by Kinoshita. We do not know the exact reason of the difference, but it is possible that the values of the planetary masses that Nakano's and Kinoshita's catalogues adopt are slightly different from others.

## Comparison of other orbital elements

The panels 27-31 in the central box show the comparison results of other orbital elements than $a_{orig}$ between Krolikowska and Horizons.

- 27: eccentricity, 28: inclination (deg), 29: argument of perihelion (deg), 30: longitude of ascending node (deg), and 31: perihelion distance (au). All the points have uncertainties in the vertical direction given in Krolikowska's catalogue.
- We see very good agreement for these orbital elements, particularly in the panels 28-31. Even in the panel for eccentricity (27), we see no systematic difference between the two catalogues except for very few comets that are on hyperbolic orbits.

## Uncertainties of the Horizons ephemeris

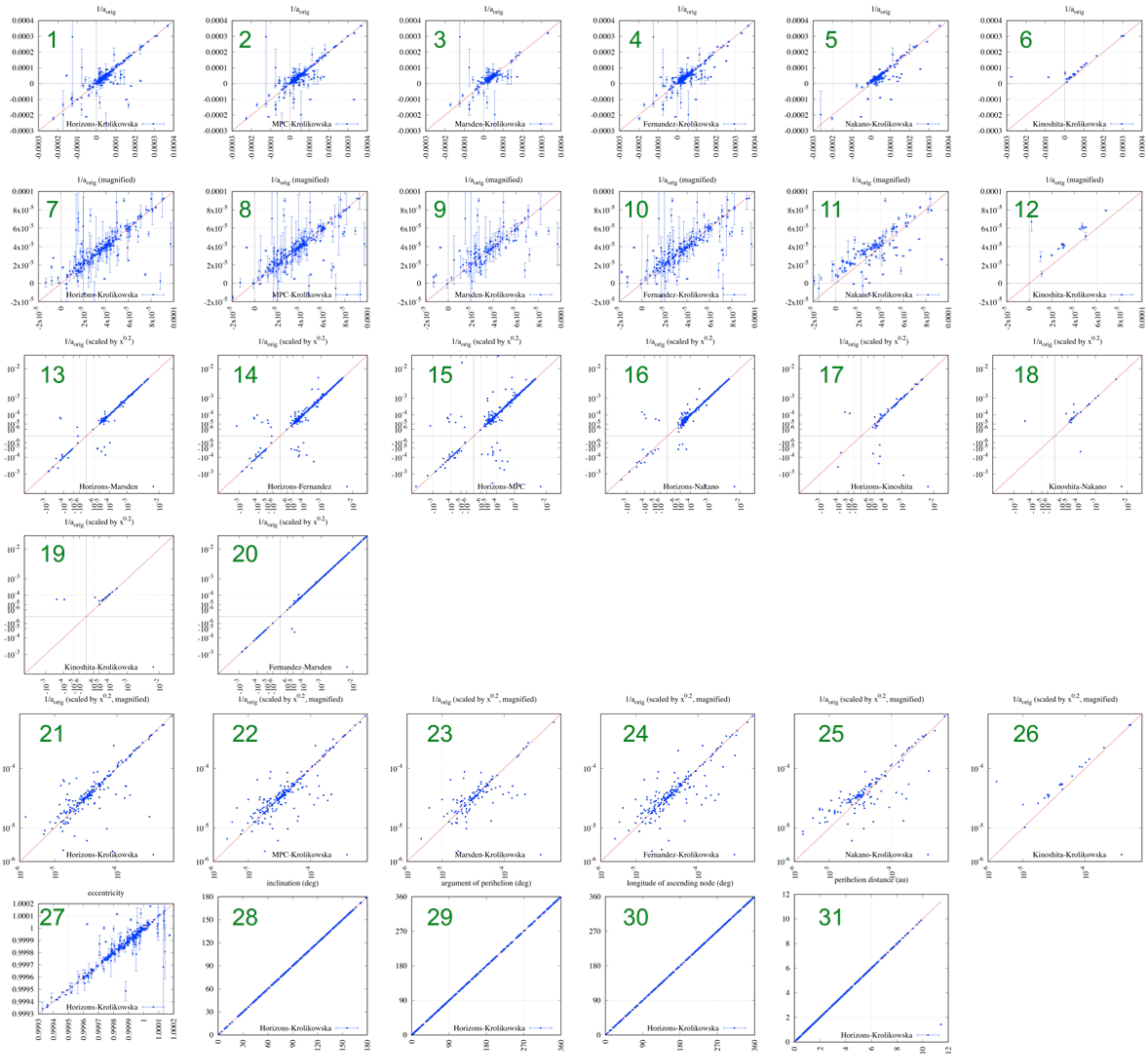
- Currently the Horizons ephemeris does not provide uncertainties in orbital elements. However, recently (~2018) it acquired a functionality to yield Cartesian positional and velocity uncertainties for orbital solutions for some objects in the form of (x, y, z, vx, vy, vz, dx, dy, dz, dvx, dvy, dvz) where dA is a 1-sigma uncertainty of the quantity A. We estimated uncertainties of the cometary original orbital elements including $a_{orig}$ from the uncertainties of the Cartesian positions and velocities with 1-sigma. We show a series of results in the panels in the rightmost box. Go there for the details.

## Conclusion

- In the statistical viewpoint, we see practically no systematic difference of $1/a_{orig}$ given by Krolikowska's catalogue and that given by Horizons, MPC, and Marsden's catalogue within the range of their uncertainties. We see an even better agreement between the values given by Krolikowska and by Horizons in other orbital elements.
- Therefore we conclude that **we do not particularly need to rely on Krolikowska's catalogues in statistical studies of the Oort Cloud cometary dynamics**. **Rather, we are inclined to use the ephemeris given by Horizons/JPL** that includes a much larger number of comet samples than Krolikowska's catalogues do. The number of samples greatly matters in this line of studies where we are still suffuring from the deficit of comet samples.

## COMPARISON OF 1/A$^{orig}$ BETWEEN CATALOGUES

The panels 1-26 in this box show comparisons of $1/a_{orig}$ between the catalogues in various scales. All the points would be aligned to the line having the slope of 45 degrees ($y = x$, denoted in red) when any pair of catalogues yields exactly the same $1/a_{orig}$ values for each comet.

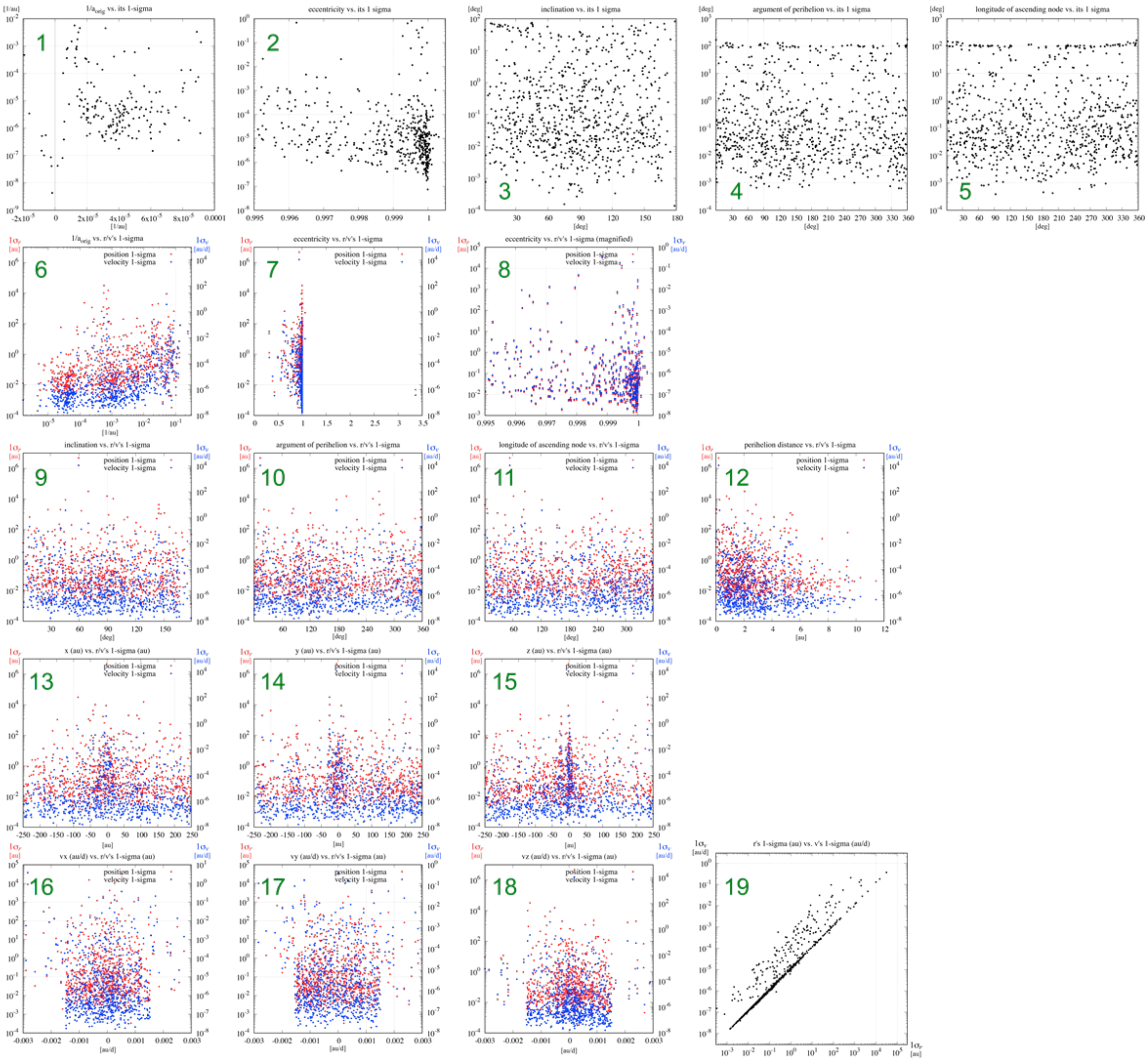


A higher resolution PDF file of the panels is available on this webpage. (https://www.cfca.nao.ac.jp/~tito/tmp/jpgu2020/ih-JpGU2020-fig1.pdf)

- The panels 1-6 are linear in both the horizontal and vertical axes. 1: Horizons-Krolikowska, 2: MPC-Krolikowska, 3: Marsden-Krolikowska, 4: Fernandez-Krolikowska, 5: Nakano-Krolikowska, and 6: Kinoshita-Krolikowska.
- The panels 7-12 are the magnified versions of 1-6. These twelve panels have uncertainties only along the vertical direction, i.e. showing the $1/a_{orig}$ uncertainty that Krolikowska's catalogues yield.
- The panels 13-20 are another variants of the magnified versions whose axis range is scaled to $(1/a_{orig})^{0.2}$. This scaling is for showing the details of the data points that are very close to $1/a_{orig} = 0$ (parabolic orbits). The panels 21-16 are even closer magnification of the scaled plots to $(1/a_{orig})^{0.2}$ that enhance the data points from $10^{-5}$ to $10^{-4}$ au$^{-1}$.
- The panels 27-31 show comparisons of other orbital elements between Horizons and Krolikowska. All the panels include vertical errorbars that Krolikowska's catalogues give. 27: eccentricity, 28: inclination (degree), 29: argument of perihelion (degree), 30: longitude of perihelion (degree), 31: perihelion distance (au).

## UNCERTAINTIES OF THE HORIZONS EPHEMERIS

Currently the Horizons/JPL ephemeris provides positional and velocity uncertainties for orbital solutions of ~800 comets in the Cartesian coordinates in the form of ($A$, d$A$) where d$A$ is a 1-sigma uncertainty of the quantity $A$. More specifically speaking, $A$ is either of the positional component x, y, z or the velocity components vx, vy, vz. We calculated the uncertainties of orbital elements from the dataset of (x, y, z, vx, vy, vz; dx, dy, dz, dvx, dvy, dvz). The number of the comets we deal with here is 800. This is the number of C/* comets whose positional and velocity uncertainty Horizons yields as of June 23, 2020.

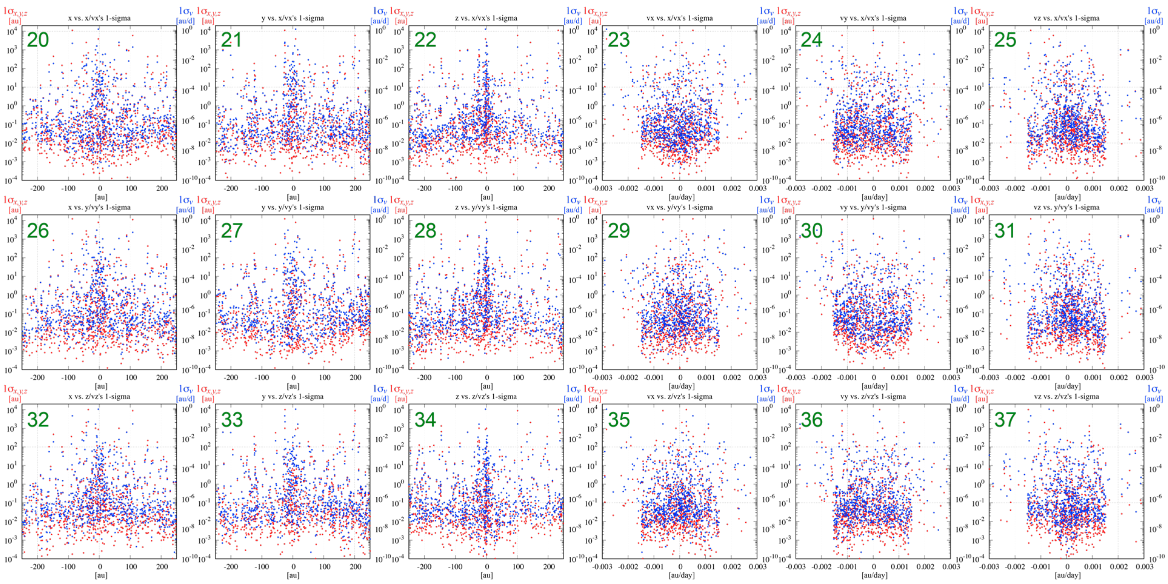


A higher resolution PDF file of the panels is available on this webpage. (https://www.cfca.nao.ac.jp/~tito/tmp/jpgu2020/ih-JpGU2020-fig2.pdf)

Here is what we actually did for our purpose. First we prepare $3^6 = 729$ kinds of Cartesian positions and velocities of each comet. The 729 combination comes from (x || x+dx || x-dx) * (y || y+dy || y-dy) * (z || z+dz || z-dz) * (vx || vx+dvx || vx-dvx) * (vy || vy+dvy || vy-dvy) * (vz || vz+dvz || vz-dvz). Note that "||" denotes "or". Then, we convert the 729 combinations of the position and the velocity into the 729 sets of the six orbital elements ($a$, $e$, $I$, $\omega$, $\Omega$, $l$). For each of the set of the obtained orbital elements, we calculate the variation using the 729 values, and regard the variation as the 1-sigma uncertainty of the element (of the set). As for the inverse of semimajor axis, 1/a (or $1/a_{orig}$), we calculate the uncertainty of 1/a as $1/(a+\Delta a) = (1/a)(1-\Delta a/a) \sim 1/a - \Delta a/a^2$ by assuming $a < \Delta a$ where $\Delta a$ is the 1-sigma uncertainty of the semimajor axis. Although it is a crude approximation, this tells us the order of magnitude of the orbital element uncertainties that current Horizons' ephemeris yields.

- The panel 1 in this box shows the dependence of the 1-sigma uncertainty of $1/a_{orig}$ on $1/a_{orig}$ itself in the range from -0.00005 to +0.0001 au$^{-1}$. The horizontal range is equivalent to that in the panel 7 in the central box where we compared the $1/a_{orig}$ values from Krolikowska's catalogue and those from Horizons' ephemeris. As we see in the panel 1 here, most comets have the $1/a_{orig}$ uncertainty of $10^{-6}$ to $10^{-5}$ au$^{-1}$, which seems as small as what Krolikowska's comet catalogue yields. There are some comets whose $1/a_{orig}$ uncertainty is large. This is typically seen in the comets whose $1/a_{orig}$ is smaller than $10^{-5}$ au$^{-1}$ (i.e. $a_{orig}$ is larger than $10^5$ au), but they are few. Also, note that our conversions from (dx, dy, dz, dvx, dvy, dvz) to the uncertainties of orbital elements such as $\Delta(1/a_{orig})$ does not consider covariance matrix: We just assume that dx, dy, dz, dvx, dvy, dvz are all independent. This is partly because we do not know the exact covariance matrix for each comet. Therefore within the limit of our assumptions, we conclude that the uncertainties of cometary $1/a_{orig}$ that Horizons' ephemeris yields is as small as those given in Krolikowska's catalogues.

- The panel 2 shows the 1-sigma uncertainties of eccentricity and its dependence on eccentricity itself. We can compare it with the panel 27 in the central box where we see the 1-sigma uncertainties of comet's eccentricity given in Krolikowska's catalogue. In the region of very large eccentricity such as $e > 0.9995$, the 1-sigma uncertainties are about $10^{-4}$ to $10^{-7}$ (except for few comets that have large uncertainties of $10^{-3}$ to $10^{0}$). Again, these values seem as small as what Krolikowska's catalogue gives.
- The panels 3,4,5 show the 1-sigma uncertainties of inclination $I$, argument of perihelion $\omega$, and longitude of ascending node $\Omega$, respectively. We can roughly identify their median values of the distributions around $10^{-1}$ to $10^{-2}$ degrees. Thus we should call them very small. But we also recognize some fraction of comets having the 1-sigma uncertainties as large as $10^{2}$ degrees, particularly in argument of perihelion and longitude of ascending node. We do not know its exact reason yet. But again we should recall that our estimate on the uncertainties or orbital elements assumes that (dx, dy, dz, dvx, dvy, dvz) are totally independent from each other. Validating or invalidating this assumption is one of our important future tasks.
- The panels 6-18 are about the relationship between the 1-sigma uncertainties of comets' heliocentric distance $r$ (1-sigma$_r$ au, drawn in red) and velocity $v$ (1-sigma$_v$ au/day, drawn in blue) on various parameters and orbital elements. $r$ and $v$ are defined as $r = \sqrt{x^2+y^2+z^2}$, $v = \sqrt{vx^2+vy^2+vz^2}$, respectively. The 1-sigma$_r$ and 1-sigma$_v$ are directly calculated from what Horizons gives; we have not intervened them with any conversions or transformations. 6: $1/a_{orig}$ (au$^{-1}$) and 1-sigma$_{r,v}$, 7: eccentricity and 1-sigma$_{r,v}$, 8: eccentricity and 1-sigma$_{r,v}$ (magnified), 9: inclination (deg) and 1-sigma$_{r,v}$, 10: argument of perihelion (deg) and 1-sigma$_{r,v}$, 11: longitude of ascending node (deg) and 1-sigma$_{r,v}$, 12: perihelion distance (au) and 1-sigma$_{r,v}$, 13: x (au) and 1-sigma$_{r,v}$, 14: y (au) and 1-sigma$_{r,v}$, 15: z (au) and 1-sigma$_{r,v}$, 16: vx (au/day) and 1-sigma$_{r,v}$, 17: vy (au/day) and 1-sigma$_{r,v}$, and 18: vz (au/day) and 1-sigma$_{r,v}$. The final panel (19) is about the relation between 1-sigma$_r$ and 1-sigma$_v$.



A higher resolution PDF file of the panels is available on this webpage. (https://www.cfca.nao.ac.jp/~tito/tmp/jpgu2020/ih-JpGU2020-fig3.pdf)

- The panels 20-37 are about the relationship between the 1-sigma uncertainties of comet's positional components x, y, z (au, drawn in red) and the velocity components vx, vy, vz (au/day, drawn in blue) on x, y, z, vx, vy, vz themselves. They are denoted as 1-sigma $_x$ 1-sigma$_y$, 1-sigma$_z$, 1-sigma$_{vx}$, 1-sigma$_{vy}$, 1-sigma$_{vz}$. An interesting fact seen in the panels is that the uncertainties become substantially large when the positional components are nearly zero (the panels 20-22, 26-28, 32-34). On the other hand, there is no remarkable dependency on the velocity components. We are not sure about how this difference takes place, but we can also say that this tendency does not pose any serious threats on the conclusion of this study.

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# ABSTRACT

Nearly isotropic comets with very long orbital period are supposed to come from the Oort Cloud. Recent observational and theoretical studies have greatly revealed the dynamical nature of this cloud and its evolutionary history. However, many issues are yet to be known. Our goal is to understand current structure of this cloud as well as its dynamical origin. For estimating the current structure of the Oort Cloud, key information lies in the original orbit of the Oort Cloud new comets (OCNCs) that are defined at a distance where these objects do not receive gravitational perturbation from major planets (such as at rg = 250 au from the Sun before comets enter into the planetary region). There have been several attempts to obtain OCNC's original orbits, but it never has been an easy task. This requires numerical orbit propagation of the observed comets with high accuracy including perturbation from major disturbing bodies. In addition, non-gravitational forces often play significant roles here. First and foremost, the orbit determination of OCNC includes substantially large uncertainty because of limited number of observational arcs and very large eccentricity of the comets (~1). Here we show our preliminary result of comparison of various catalogues of OCNCs' original orbital elements at rg = 250 au: So-called the Warsaw catalogues by Krolikowska, the ephemeris given by MPC (Minor Planet Center), that given by Horizons/JPL, and others calculated by a few individuals (Marsden, Kinoshita, and Nakano). The resulting orbits that these catalogues yield are overall similar, but sometimes they are starkly different by reasons yet to be known. Through a series of plots with a help of our own orbit propagation using numerical and analytic methods, we give considerations on which catalogue yields the information that is the most significant (or the most fundamental) for understanding structure, origin, and evolution of the Oort Cloud.