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

II. Different solutions from different observations

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abstract

Recent observational and theoretical studies have greatly revealed the dynamical nature of the Oort 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 (in this study at $r = 250$ 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 ($e \sim 1$). Here I show our result of comparison of various catalogues of OCNCs' original orbital elements at $r = 250$ au: So-called the Warsaw catalogue by Krolikowska, the ephemeris given by MPC (Minor Planet Center), and that given by Horizons/JPL. In particular, I pay attention to the difference of the original semimajor axis among the several different solutions that the Warsaw catalogue and the MPC ephemeris have in comparison with the solutions given by Horizons/JPL - such as the difference between the solution 1 in the Warsaw catalogue and the solution from Horizons/JPL, the solutions 1 and 2 in the Warsaw catalogue, the solutions 2 and 3 in the MPC ephemeris and so forth. The resulting orbits that these solutions yield look overall similar, but sometimes they show stark difference for some reason.

catalogues and ephemeris

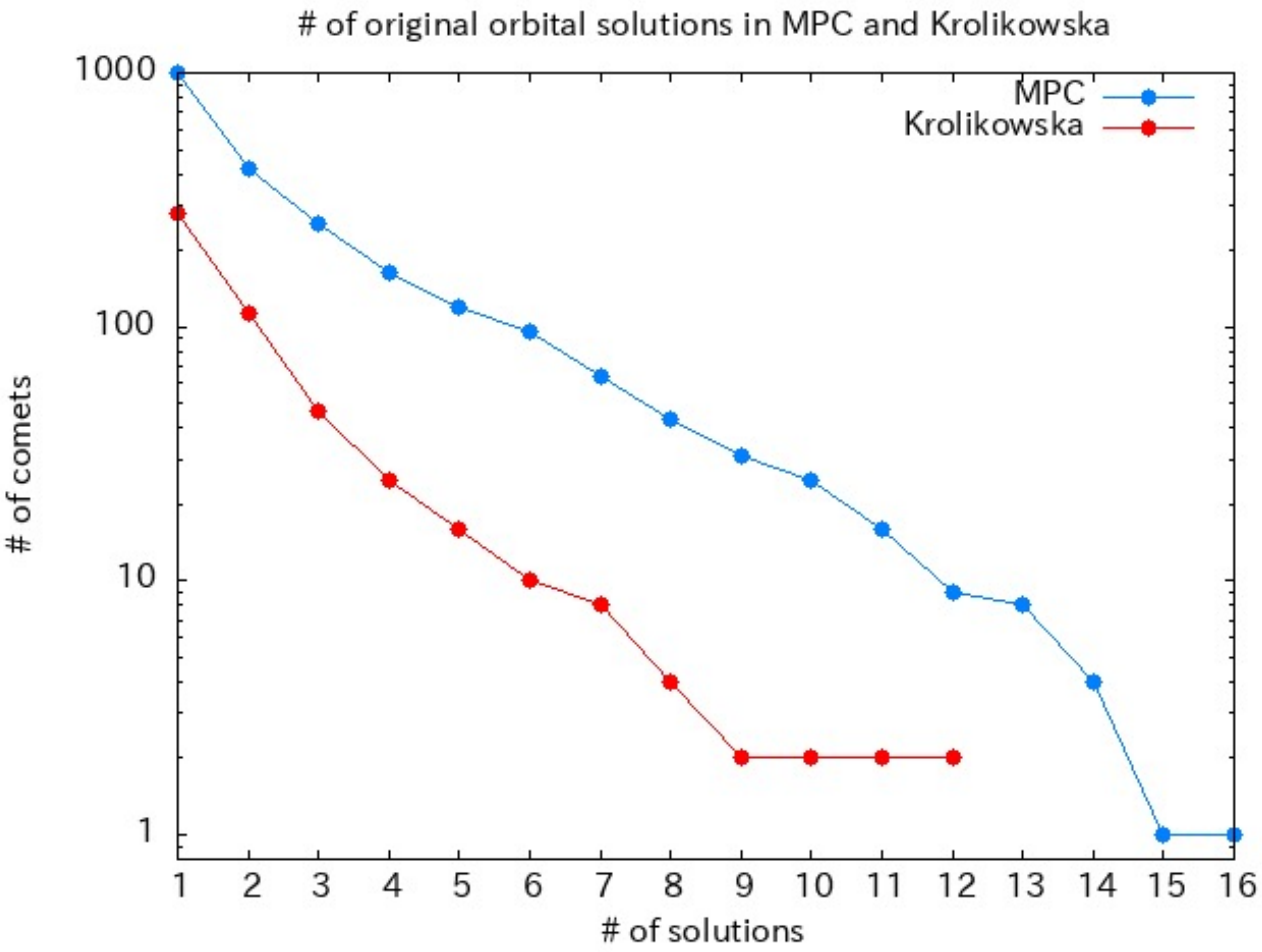
Currently, several catalogues are freely available for the original orbital elements (defined at $r = 250$ au) of the Oort Cloud comets. What we use and compare in this study is as follows:

- Malgorzata Krolikowska's series of cometary catalogues: the "Warsaw Catalogue of cometary orbits". Recently the whole dataset was summarized on a website. As for the details of the theoretical background and implementation of the calculations, see the series of her publications: Krolikowska (2014), Krolikowska+ (2014), Krolikowska and Dybczynski (2017), Krolikowska and Dybczynski (2018), and Krolikowska (2020). On the website as of 2020 May, the original orbits of 277 comets (together with their previous, current, next, and future orbits) are available with 1σ uncertainties. The series of her catalogues has been widely known and accepted as the most reliable. Note that some of the cometary orbits in these catalogues are determined with nongravitational effect, but we do not discuss this point in this work.
- The online ephemeris that MPC (Minor Planet Center) provides. This ephemeris includes 2799 "C/" comets as of 2021 January 11, and some of them are given their original semimajor axis ($1/a_{\mathrm{orig}}$) but without uncertainty values. See https://minorplanetcenter.net/ for more detail.
- The online ephemeris that Horizons/JPL provides. We can specify object 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/" comets as of 2021 January 11. Add to that, recently this ephemeris began yielding position and velocity uncertainties for orbital solutions for many comets in the form of (x, y, z, v_x, v_y, v_z; $\delta x, \delta y, \delta z, \delta v_x, \delta v_y, \delta v_z$) where δA is a 1σ uncertainty of the quantity A. See https://ssd.jpl.nasa.gov/horizons.cgi for more detail.

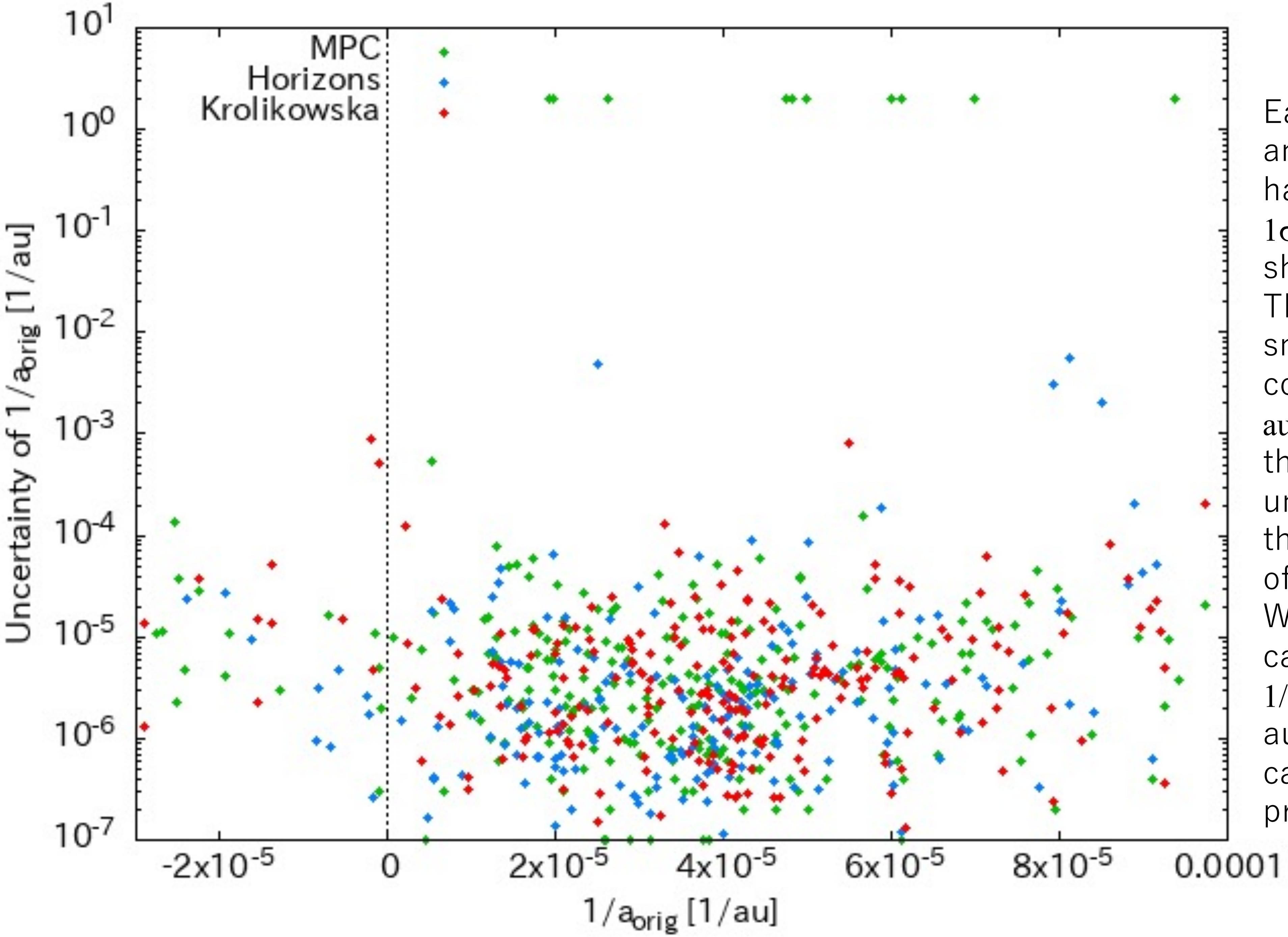
the numbers of comet samples

The numbers of the "C/" comets whose reciprocal of original semimajor axis ($1/a_{\mathrm{orig}}$) is recorded:

- Krolikowska's web catalogue : 277 (as of 2020 May)
- The online ephemeris of MPC: 993 (as of 2021 January)
- Horizons/JPL (at $r = 250$ au): 2296 (as of 2021 January)
    - In total 2898 C/ comets data are stored in Horizons. However, 602 of them are recorded at slightly closer distance from the Sun than $r = 250$ au due to the ephemeris limit that starts on A.D. 1600-Jan-01 .

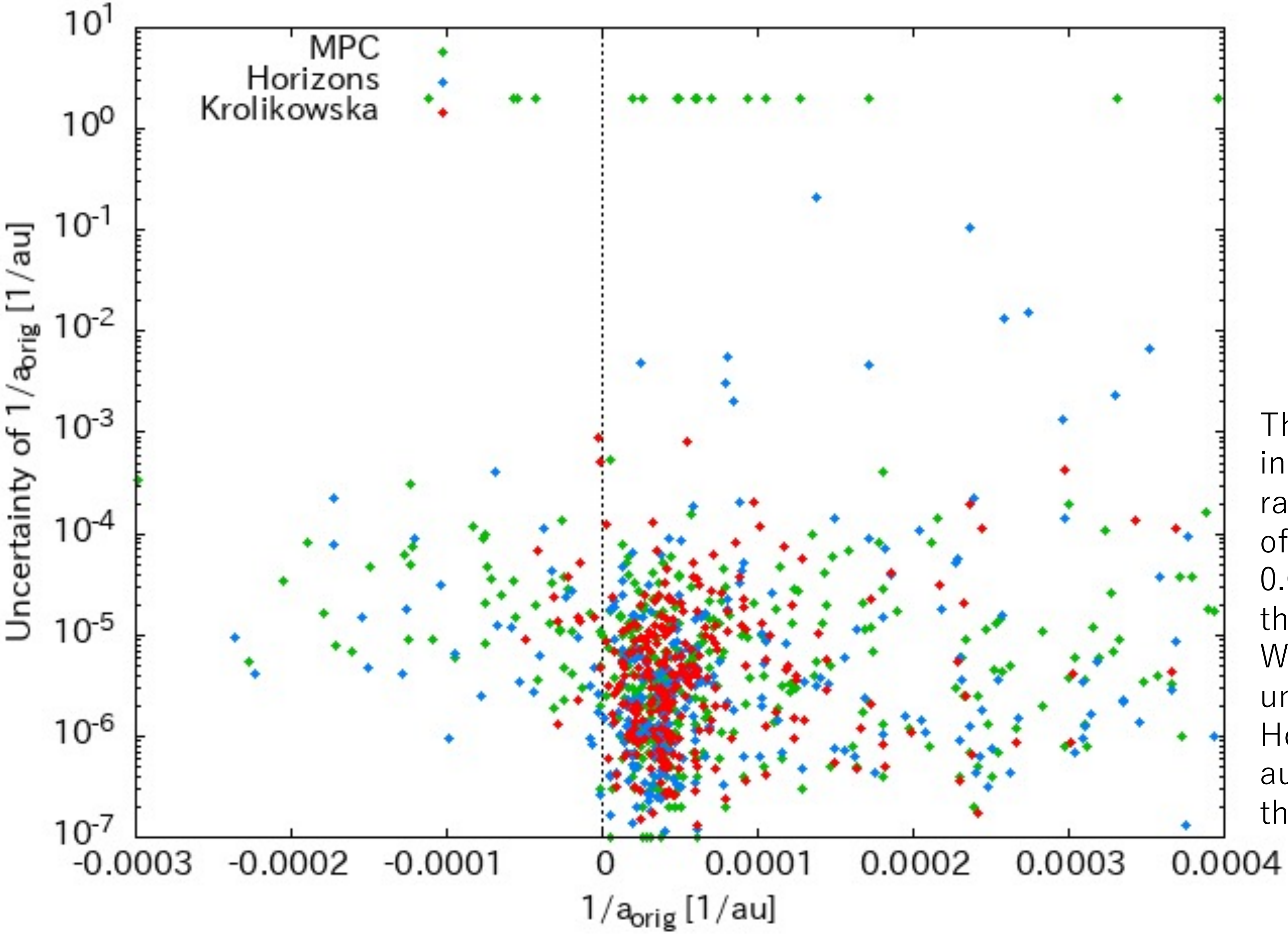


Currently, MPC stores a maximum of 16 orbital solutions for a single comet (this number can be greater in future). The blue line in the left panel shows the frequency of the number of comets for which MPC has multiple orbital solutions.
The Krolikowska catalog also stores a maximum of 12 orbital solutions for a single comet (this number can be greater in future too). The red line in the panel shows the frequency distribution.

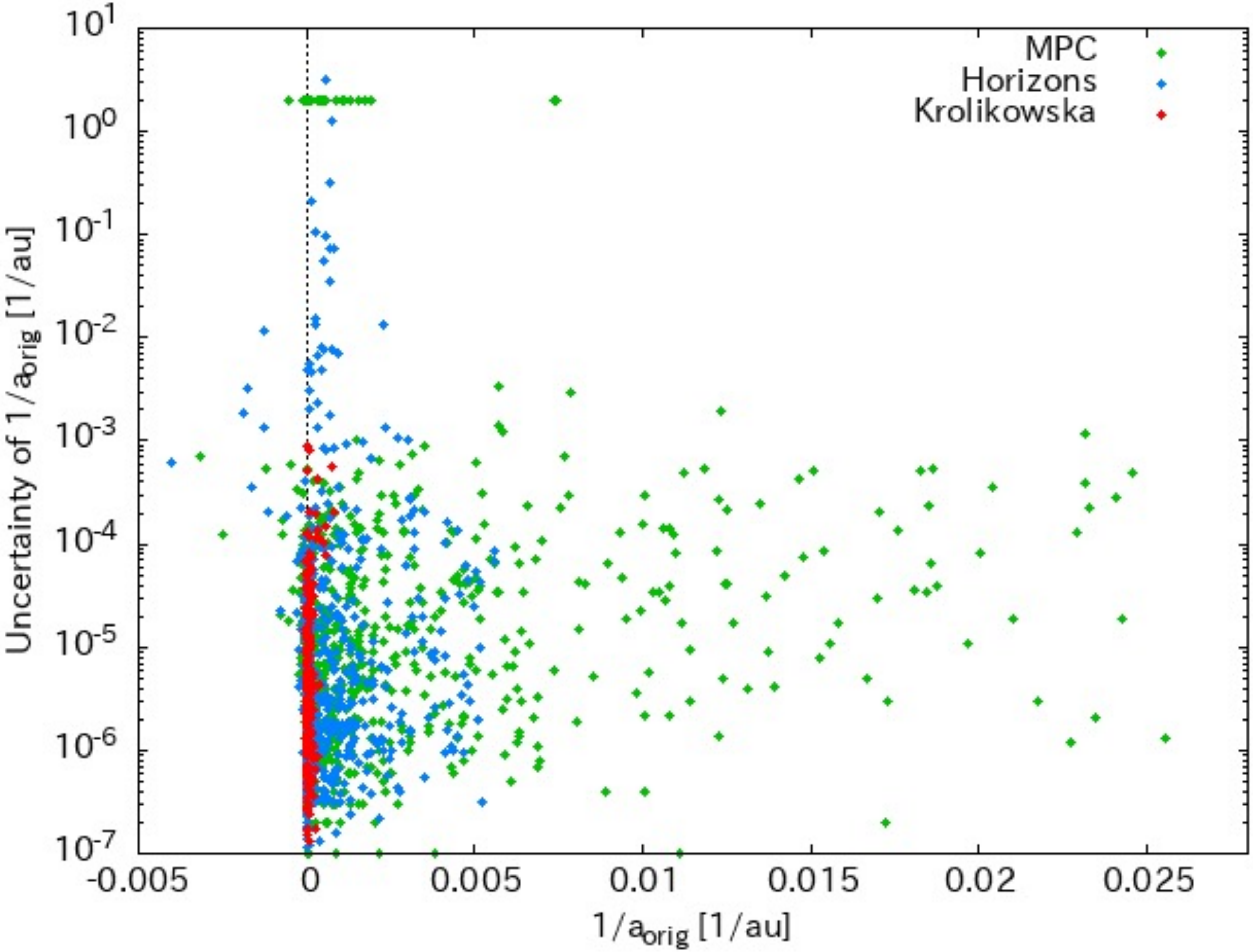


Each of the MPC, Horizons, and Krolikowka catalogues has different values of the 1σ uncertainty for $1/a_{\rm orig}$ as shown in the left panel. The values of $1/a_{\rm orig}$ is very small in the left panel: the comets have $|a_{\rm orig}| > 10000$ au . The plot indicates that the difference in the $1/a_{\rm orig}$ uncertainties among the three catalogs in this range of $1/a_{\rm orig}$ is small.

We find somewhat unusual case in MPC where the $1/a_{\rm orig}$ uncertainty reaches 2 au for several comets. This can be due to a database problem of MPC.



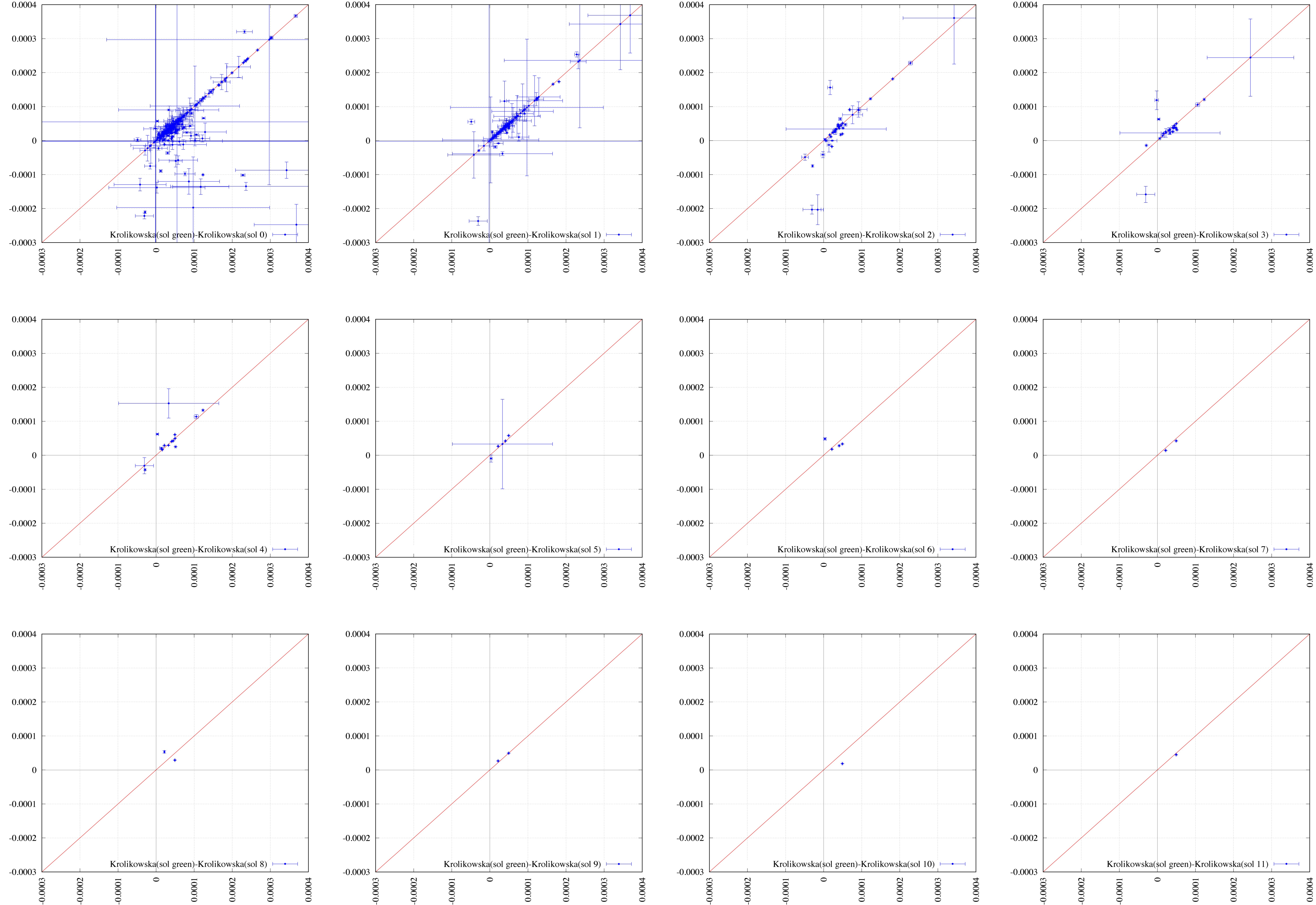
The same plot as the panel in p. 6, but the horizontal range is larger: The range of $1/a_{\rm orig}$ (from -0.0003 to 0.0004 au) is common to the panels in p. 10-15. We see some scatter of the uncertainties that the Horizons data has ($1\sigma > 10^{-3}$ au), but the number of these comets is small.



The same plot as the panels in p. 6-7, but the horizontal range is much wider. It appears that the only comets in the region $1/a_{\rm orig} > 0.005$ are those obtained from MPC. This is because the comets stored by Horizons in this range are not given orbital solutions at $r = 250$ au due to the ephemeris time limit (A.D. 1600-Jan-01 or later). If the definition of the original orbits ($r = 250$ au) can be ignored (e.g., if we accept orbital elements at $r = 240$ au), the data points from Horizons appear in very similar locations to the MPC data.

comparison: inverse of semimajor axis: $1/a_{\mathrm{orig}}$

- Krolikowska (the “green” solution) vs. other solutions (0^{th}-11^{th})
- Krolikowska (the “green” solution) vs. MPC (1^{st}-16^{th} sols)
- MPC (the 1^{st} solution) vs. other solutions (1^{st}-16^{th} sols)
- MPC (the 1^{st} solution) vs. Krolikowska (0^{th}-11^{th} sols)
- Horizons (the solution with 1σ) vs. Krolikowska (0^{th}-11^{th} sols)
- Horizons (the solution with 1σ) vs. MPC (1^{st}-16^{th} sols)

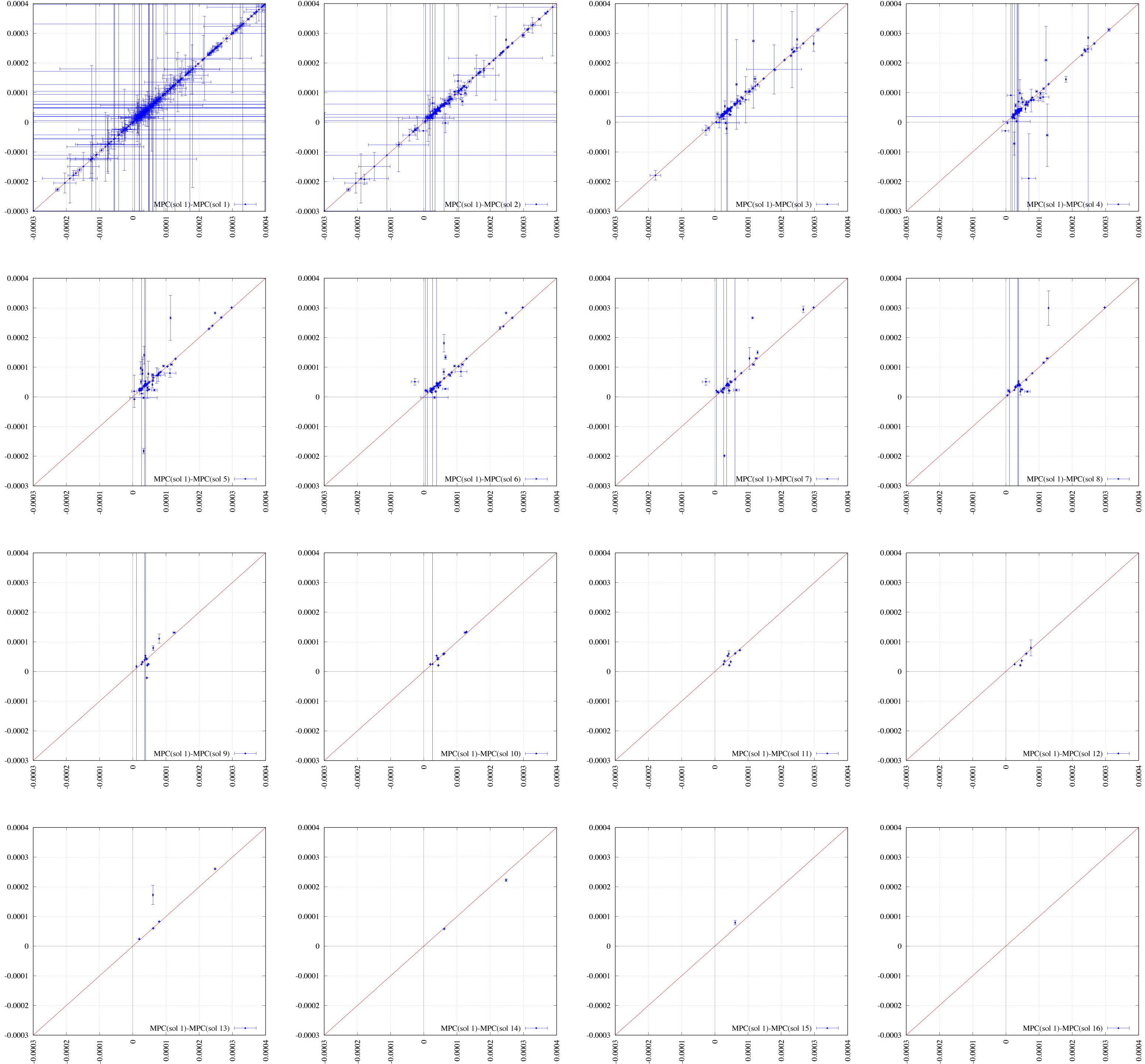


$1/a_{\mathrm{orig}}$

Krolikowska (the “green” sol) vs. other sols

The unit for both the axe is 1/au

The "green" solutions are the ones that are marked in green in Krolikowska’s catalogue webpage. They are regarded to be the most reliable among all the solutions, and we used them as a standard for comparison. Having this standard, we compared the 12 kinds of her orbital solutions. If the two solutions under comparison have the same value, the data point would be on the red line with the slope of 45° . With a few exceptions, Krolikowska's non-green solutions turned out to be consistent with the green solution.

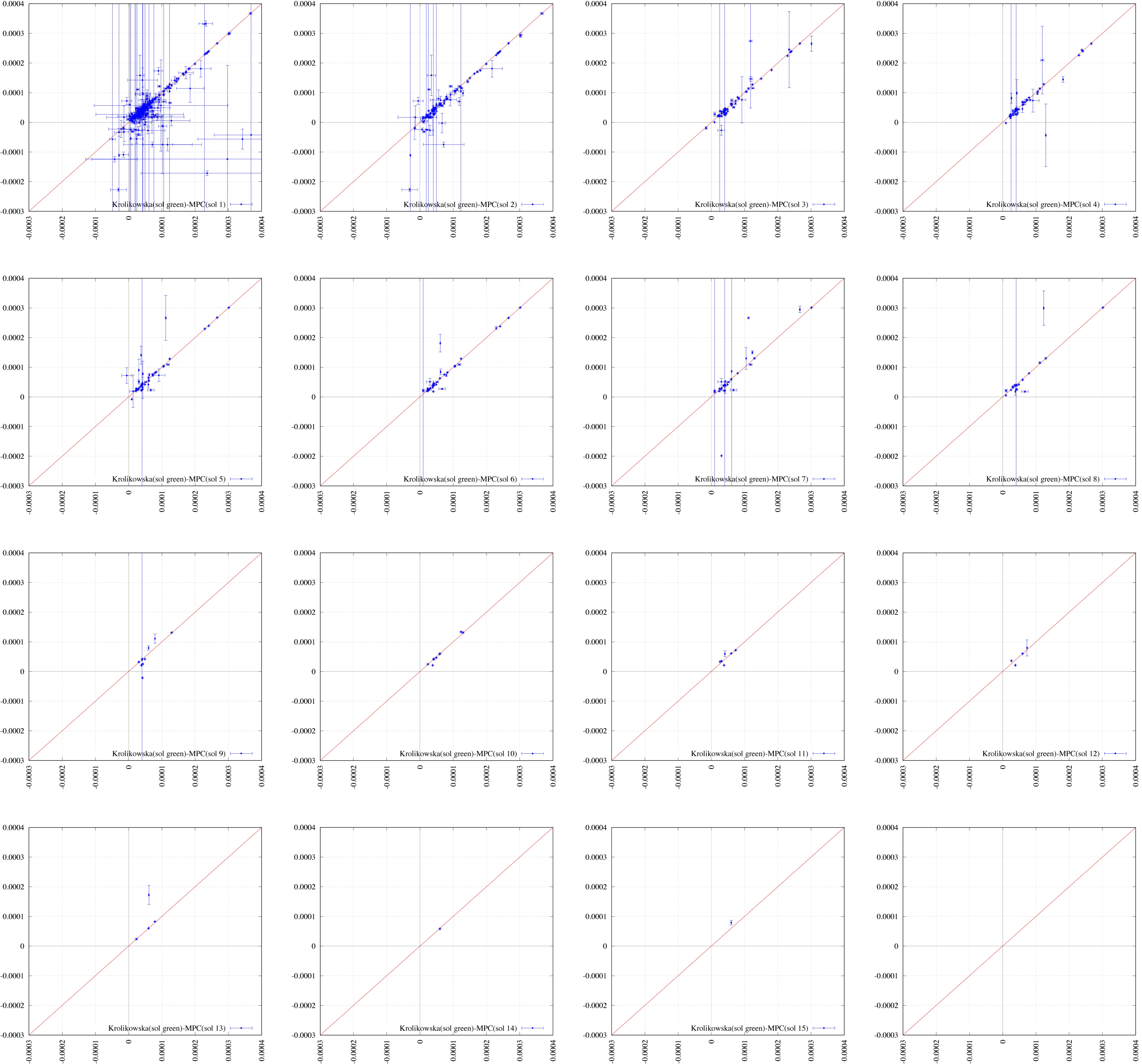


$1/a_{\mathrm{orig}}$

MPC (the 1st sol) vs. other sols

The unit for both the axe is 1/au

We plotted MPC's orbital solutions of 16 kind against its solution 1 as the standard. This means that the top left panel is comparing the same dataset (hence the plot is symmetric against the red line with 45° slope). It is noticeable that $1/a_{\mathrm{orig}}$ of a certain number of comets has substantially large uncertainties (broken database?). But other than that, we see that most of the solutions largely have the similar accuracy to each other, and they seem consistent.

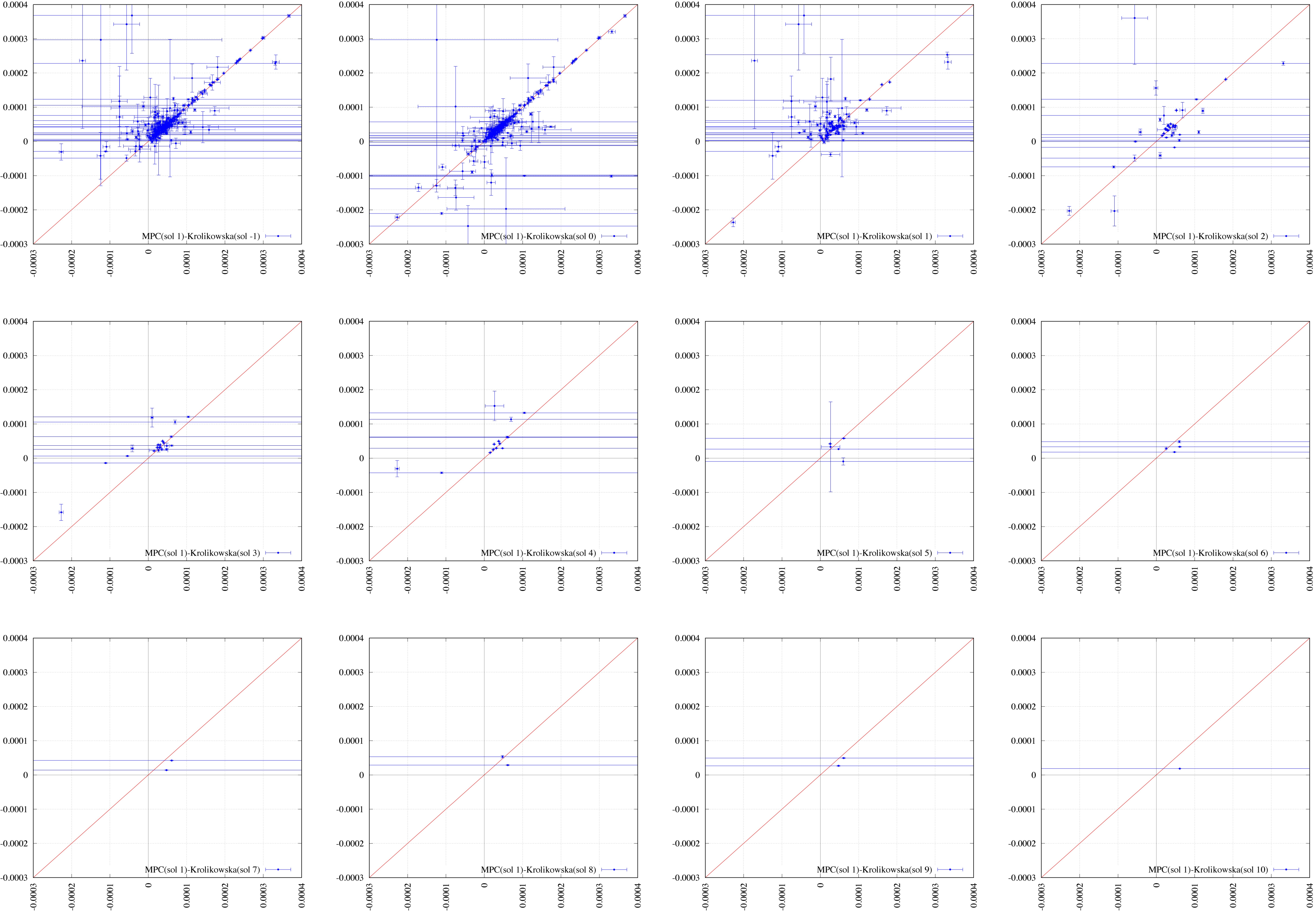


$1/a_{\mathrm{orig}}$

Krolikowska (the “green” sol) vs. MPC (1-16 sols)

The unit for both the axe is 1/au

We plotted MPC’s orbital solutions of 16 kind against Krolikowsk’s "green" solutions as the standard. Here again it is noticeable that $1/a_{\mathrm{orig}}$ of a certain number of comets in the MPC catalogue has a very large uncertainty. But other than that, the two dataset agree well within this range of $1/a_{\mathrm{orig}}$.

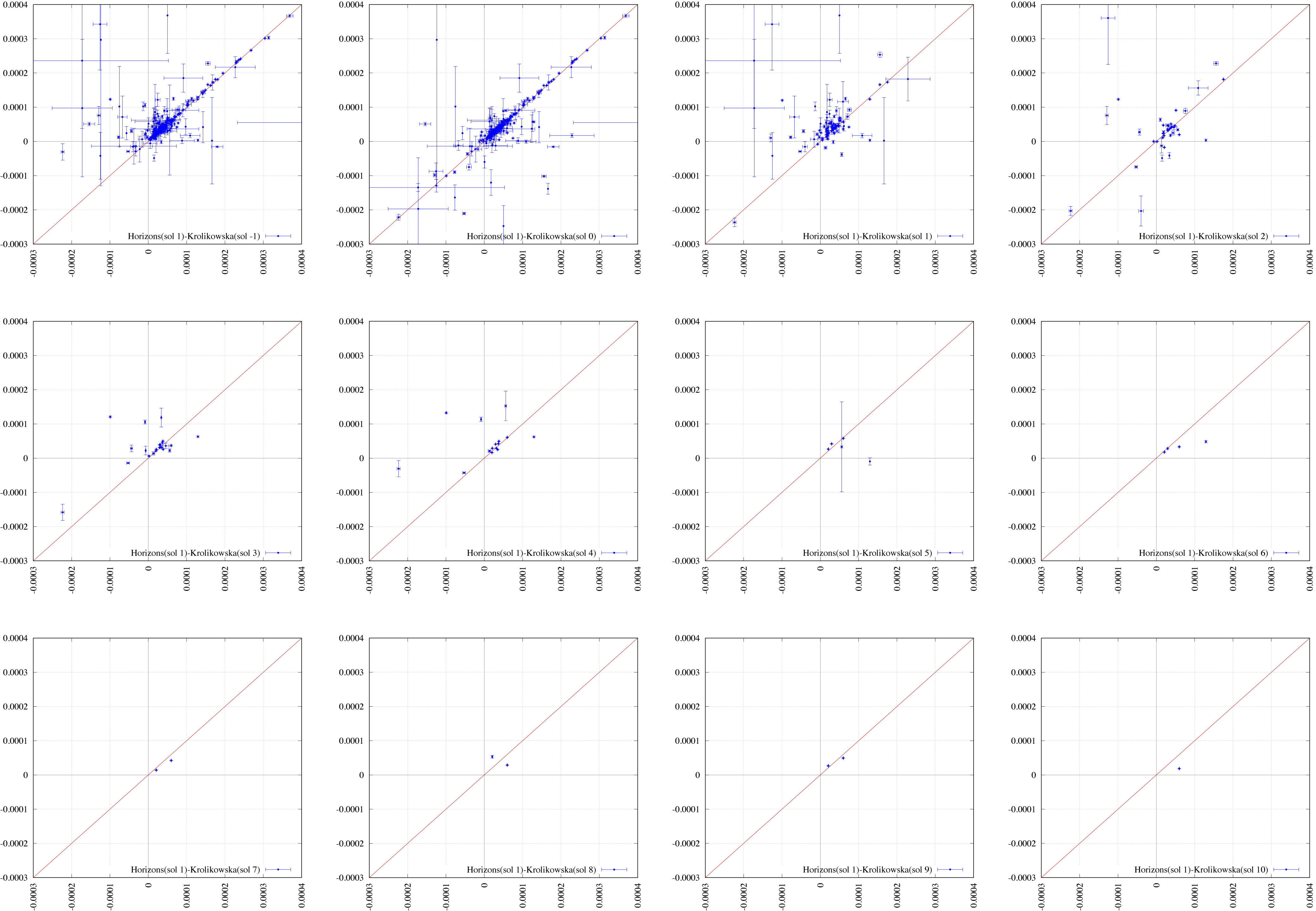


$1/a_{\rm orig}$

MPC (the 1st sol) vs. Krolikowska (0th-11th sols)

The unit for both the axe is 1/au

We compare MPC's 1st orbital solution with Krolikowska's 12 different solutions. The large uncertainties of some comets in the MPC's orbital solutions are still noticeable, but there are no other fatal differences. In a word, MPC's 1st (the most typical) solutions and Krolikowska's 12 sets of solutions are consistent within this range of $1/a_{\rm orig}$.

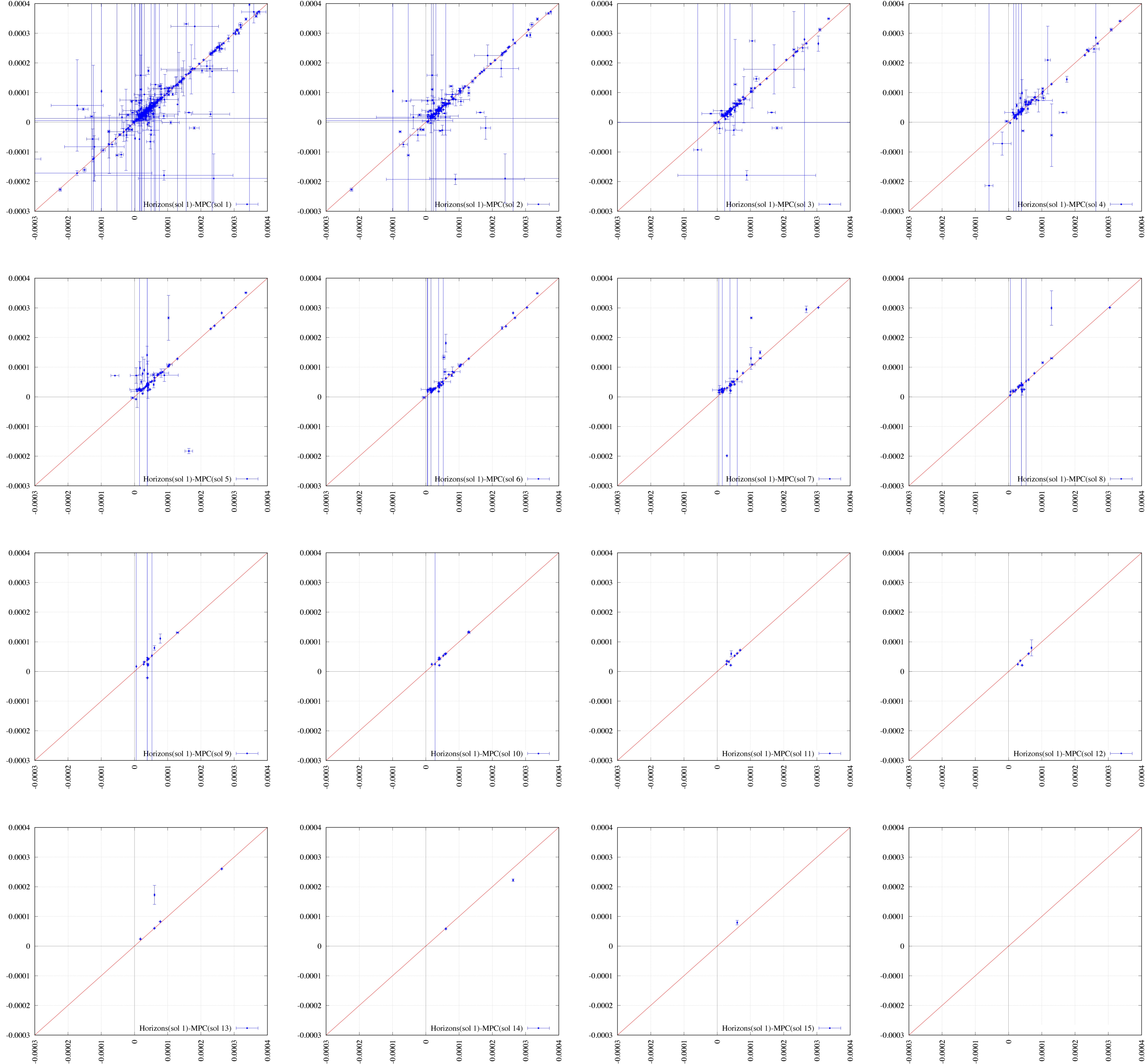


$1/a_{\mathrm{orig}}$

Horizons (w/ 1σ) vs. Krolikowska (0th-11th sols)

The unit for both the axe is 1/au

Horizons gives just one kind of orbital solution for each object. Uncertainty of orbital elements is not given either. Recently, however, Horizons has been able to yield the standard deviation of the Cartesian coordinates. Using the standard deviation, we calculated the uncertainty of $1/a_{\mathrm{orig}}$ and compared the solutions with Krolikowska's 12 different solutions: the green solution (upper left) and the solutions 0-10. Comparison with the green solution (top left) shows that Krolikowska categorizes some comets as $1/a_{\mathrm{orig}} > 0$ while Horizons recognize them as $1/a_{\mathrm{orig}} < 0$. But this is just about a few cases, and in others panels we find the agreement is good within this range of $1/a_{\mathrm{orig}}$.



$1/a_{\rm orig}$

Horizons (w/ 1σ) vs. MPC (1th-16th sols)

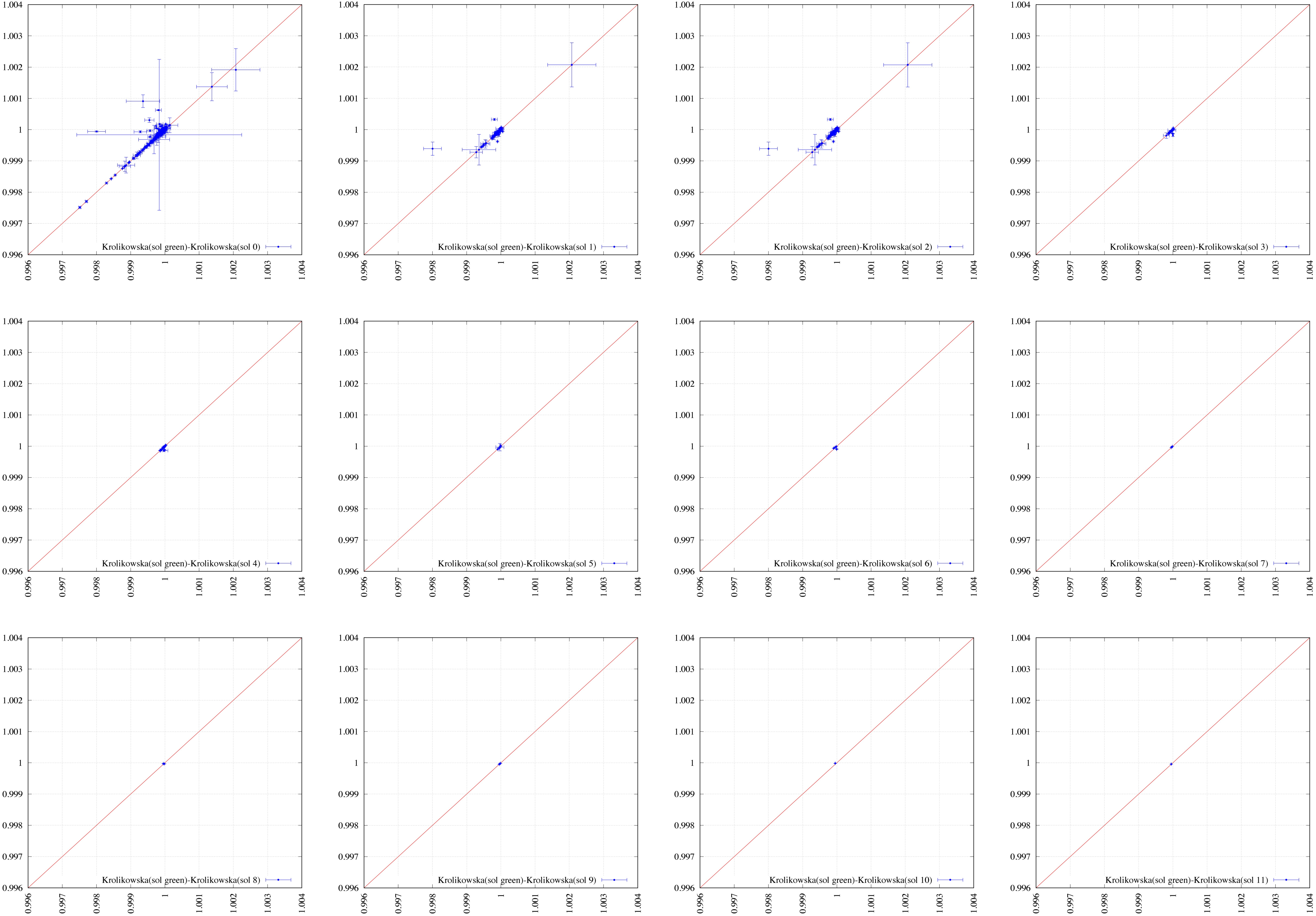
The unit for both the axe is 1/au

We plotted MPC's 16 orbital solutions against Horizon's orbital solutions. We find that some comets in both MPC and Horizons have large uncertainties, but their number is small. In general, $1/a_{\rm orig}$ of the comets included in both the ephemeris are largely consistent with each other, and the deviations from the 45° line are little within this range of $1/a_{\rm orig}$.

comparison: eccentricity: e_{orig}

- Krolikowska (the “green” solution) vs. other solutions (0-11)
- Horizons (w/o uncertainty) vs. Krolikowska (0^{th}-11^{th} sols)

  - Note that we have not calculated the error propagation of the original eccentricity from the 1σ uncertainties of the Cartesian vector coordinates (x, y, z, v_x, v_y, v_z) that Horizons yields. We will prepare it for our next presentation.
  - Note also that MPC does not provide any information about the original eccentricity.



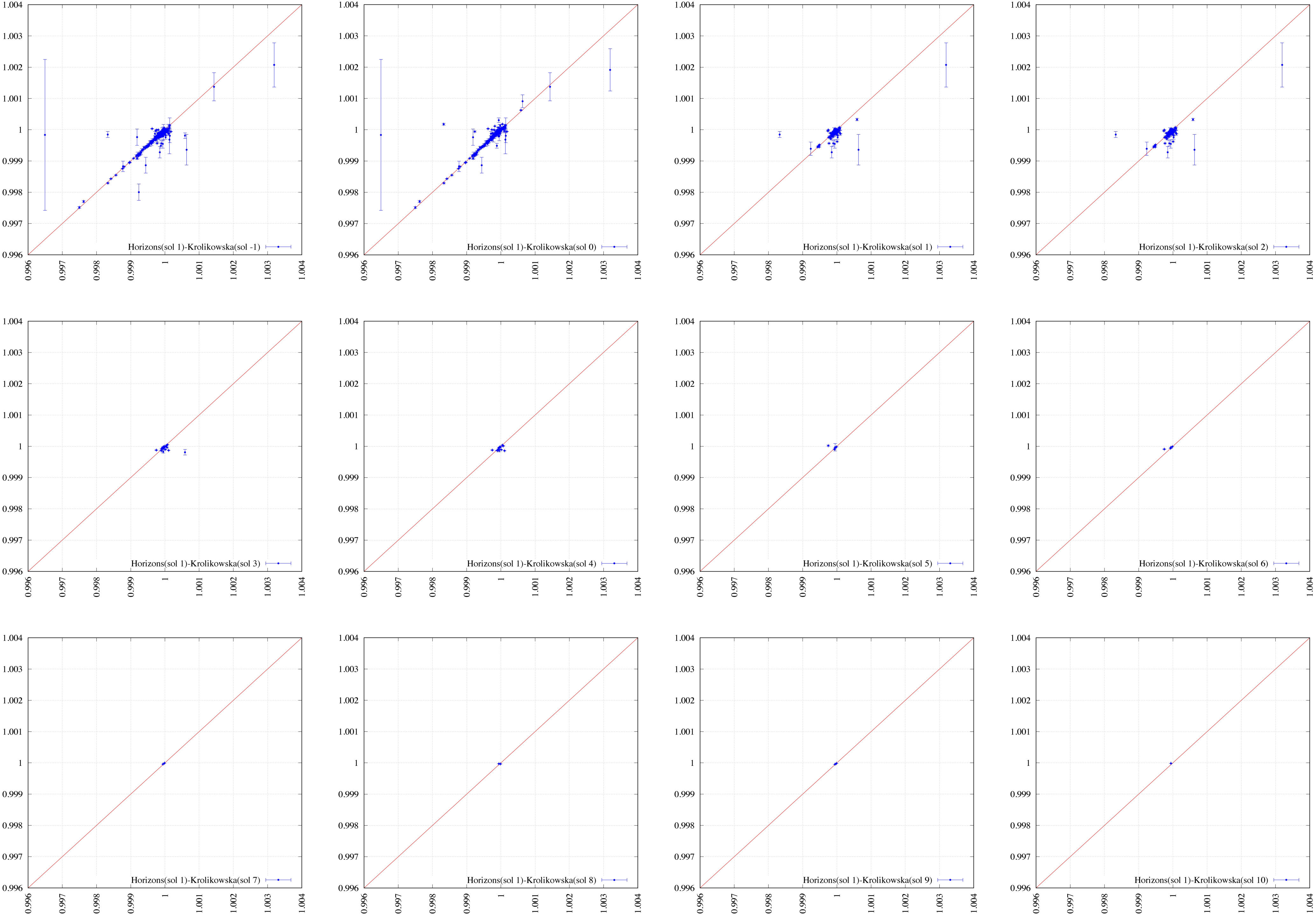
e_{orig}

Krolikowska (the "green" sol) vs. other sols

Krolikowska' "green" solution was used as the standard for comparison with her solutions 0-11. With a few exceptions, there is no significant difference between the green solution and the other solutions. We can say the two are consistent.

e_{orig}

Horizons (w/o err) vs. Krolikowska (0th-11th sols)

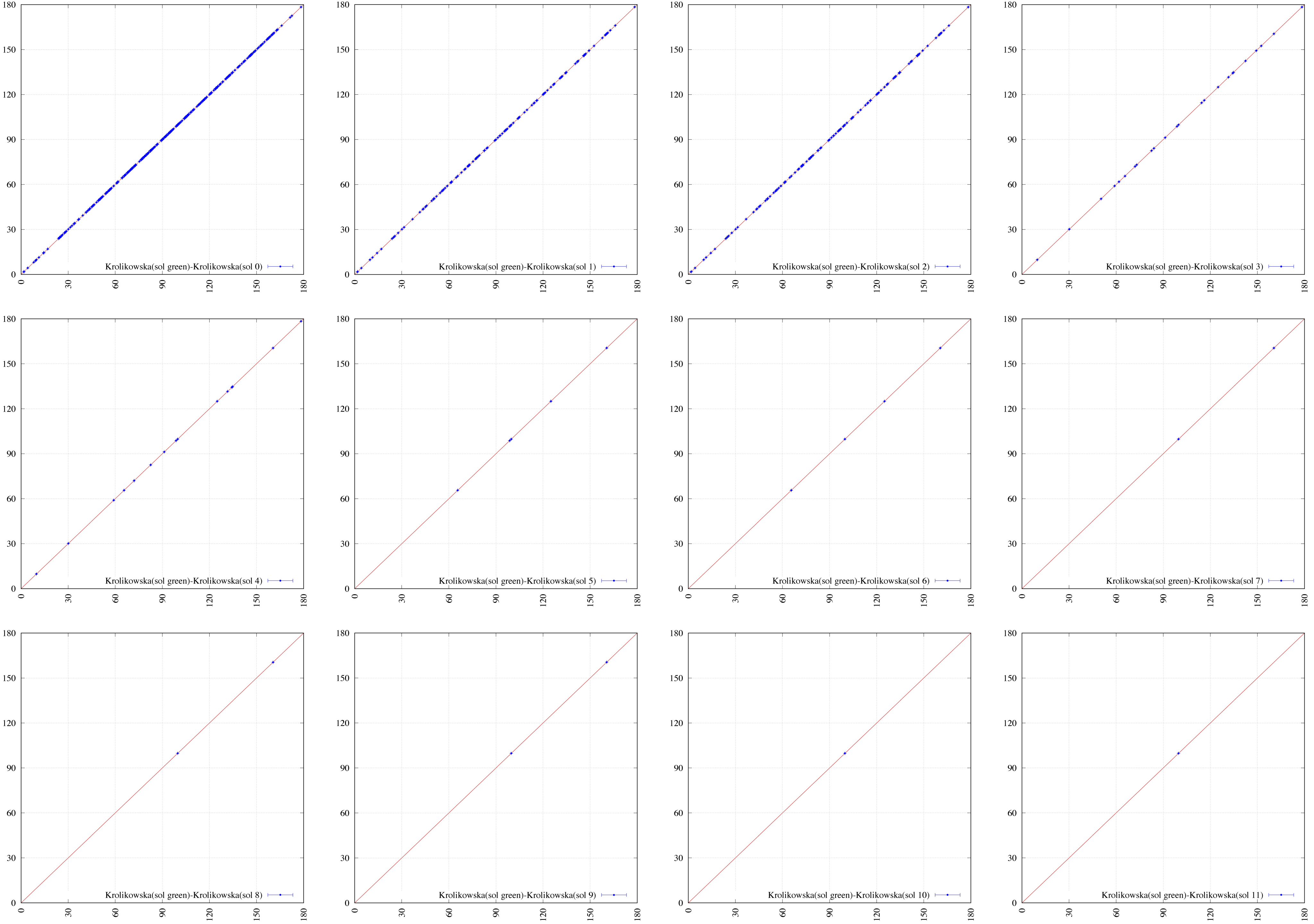


Having the solution given by Horizons as reference, we plotted Krolikowska's solutions of 12 kind (0-11). Except the few inconsistencies seen in the hyperbolic ranges ($e > 1$), we find these two sets are consistent.

comparison: inclination: I_{orig}

- Krolikowska (the “green” solution) vs. other solutions (0-11)
- Horizons (w/o uncertainty) vs. Krolikowska (0th-11th sols)

  - Note that we have not calculated the error propagation of the original inclination from the 1σ uncertainties of the Cartesian vector coordinates (x, y, z, v_x, v_y, v_z) that Horizons yields. We will prepare it for our next presentation.
  - Note also that MPC does not provide any information about the original inclination.

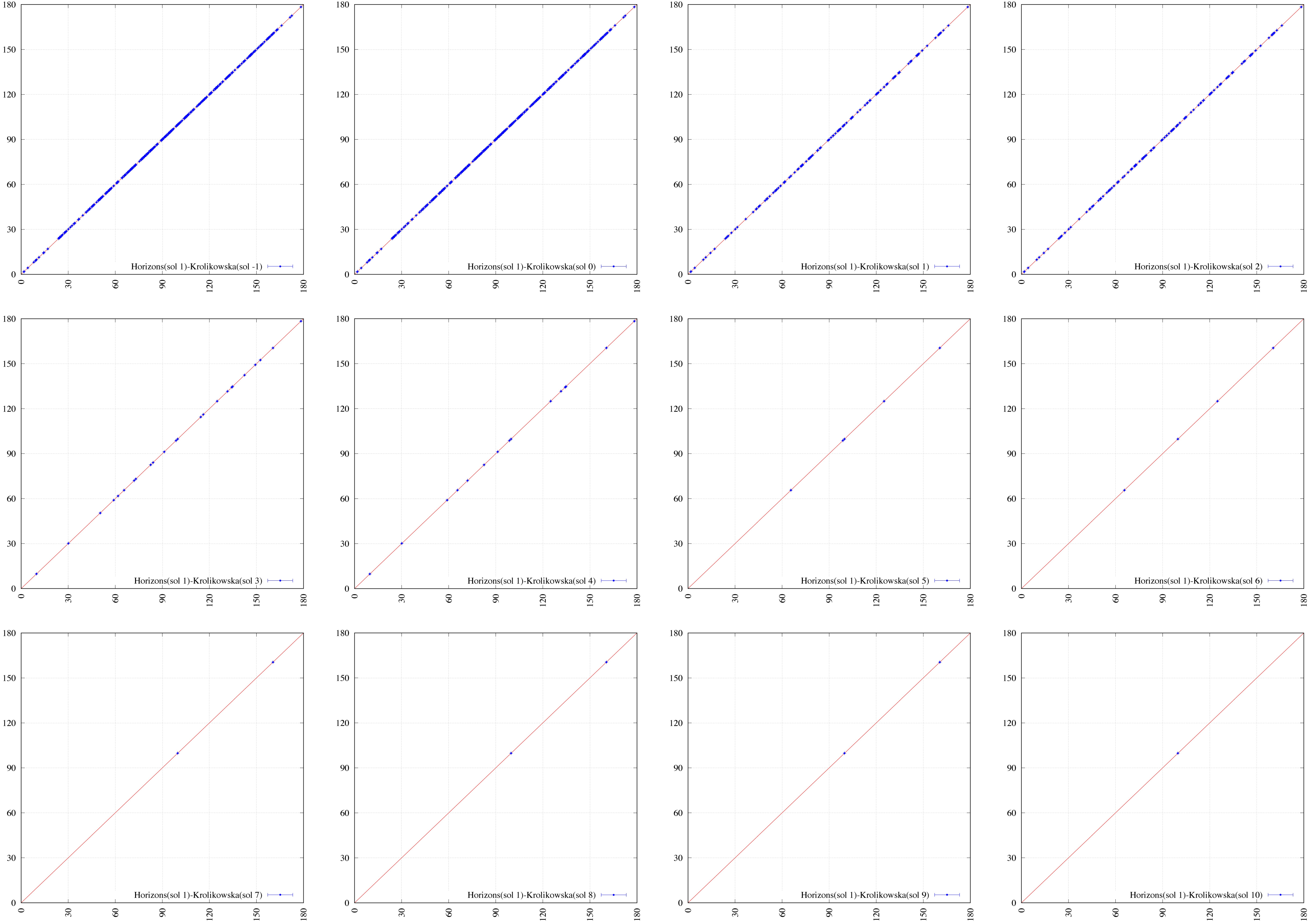


I_{orig}

Krolikowska (the “green” sol) vs. other sols

The unit for both the axe is degree

Krolikowska’ “green” solution was used as the standard for comparison with her solutions 0-11. As we see, they seem quite consistent with each other, and the magnitude of the uncertainties is very small.



I_{orig}

Horizons (w/o err) vs. Krolikowska (0th-11th sols)

The unit for both the axe is degree

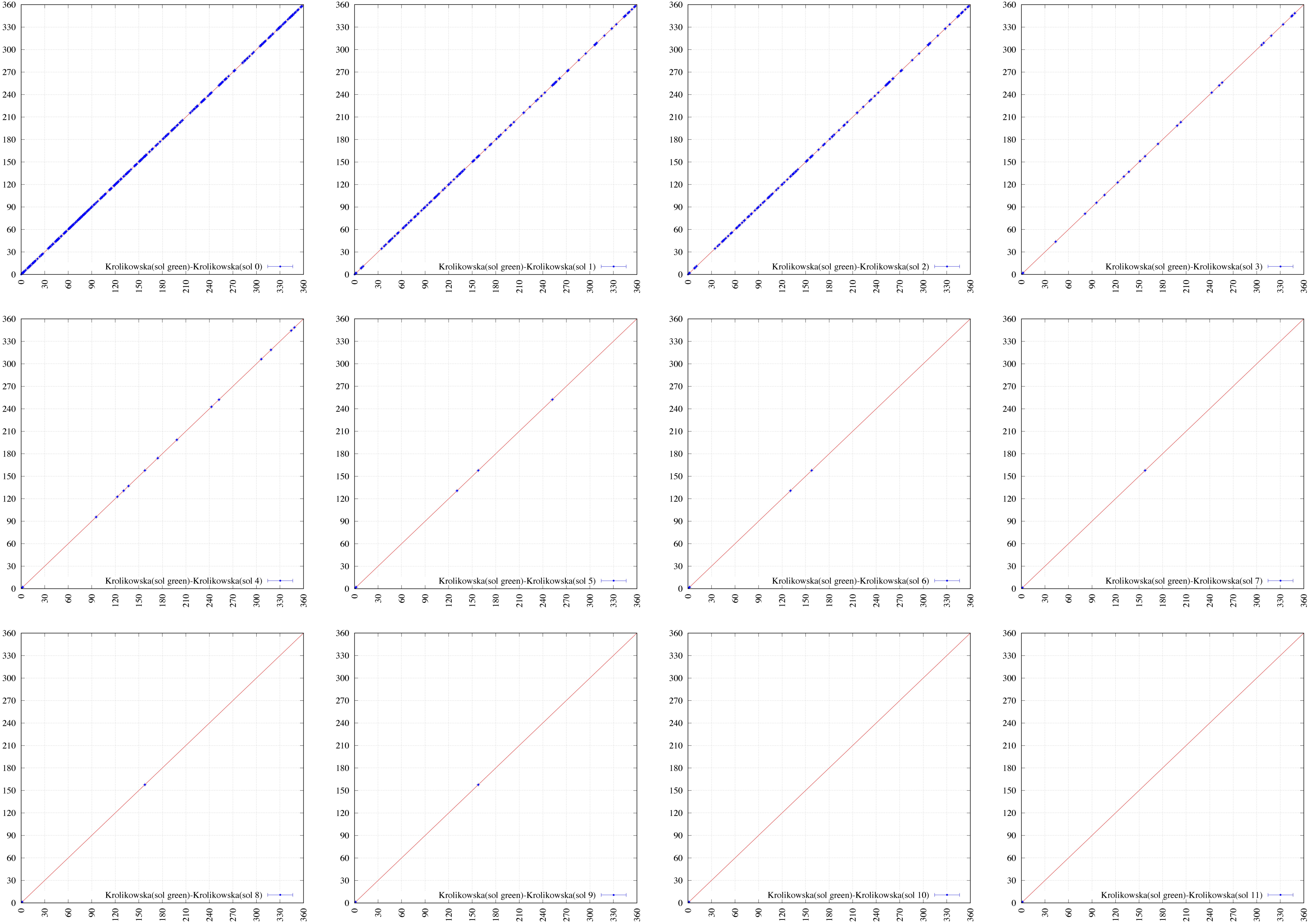
Having the solution given by Horizons as a reference, we plotted Krolikowska's solutions of 12 kind (0-11). As we see, they seem quite consistent, and the magnitude of the uncertainties is very small.

Note that the data points do not have any error bars along the horizontal axis, as we have not calculated them yet through the uncertainties included in the Cartesian coordinates given in the Horizons data.

comparison: argument of perihelion: g_{orig}

- Krolikowska (the “green” solution) vs. other solutions (0-11)
- Horizons (w/o uncertaintys) vs. Krolikowska (0th-11th sols)

  - Note that we have not calculated the error propagation of the original argument of perihelion from the 1σ uncertainties of the Cartesian vector coordinates (x, y, z, v_x, v_y, v_z) that Horizons yields. We will prepare it for our next presentation.
  - Note also that MPC does not provide any information about the original argument of perihelion.

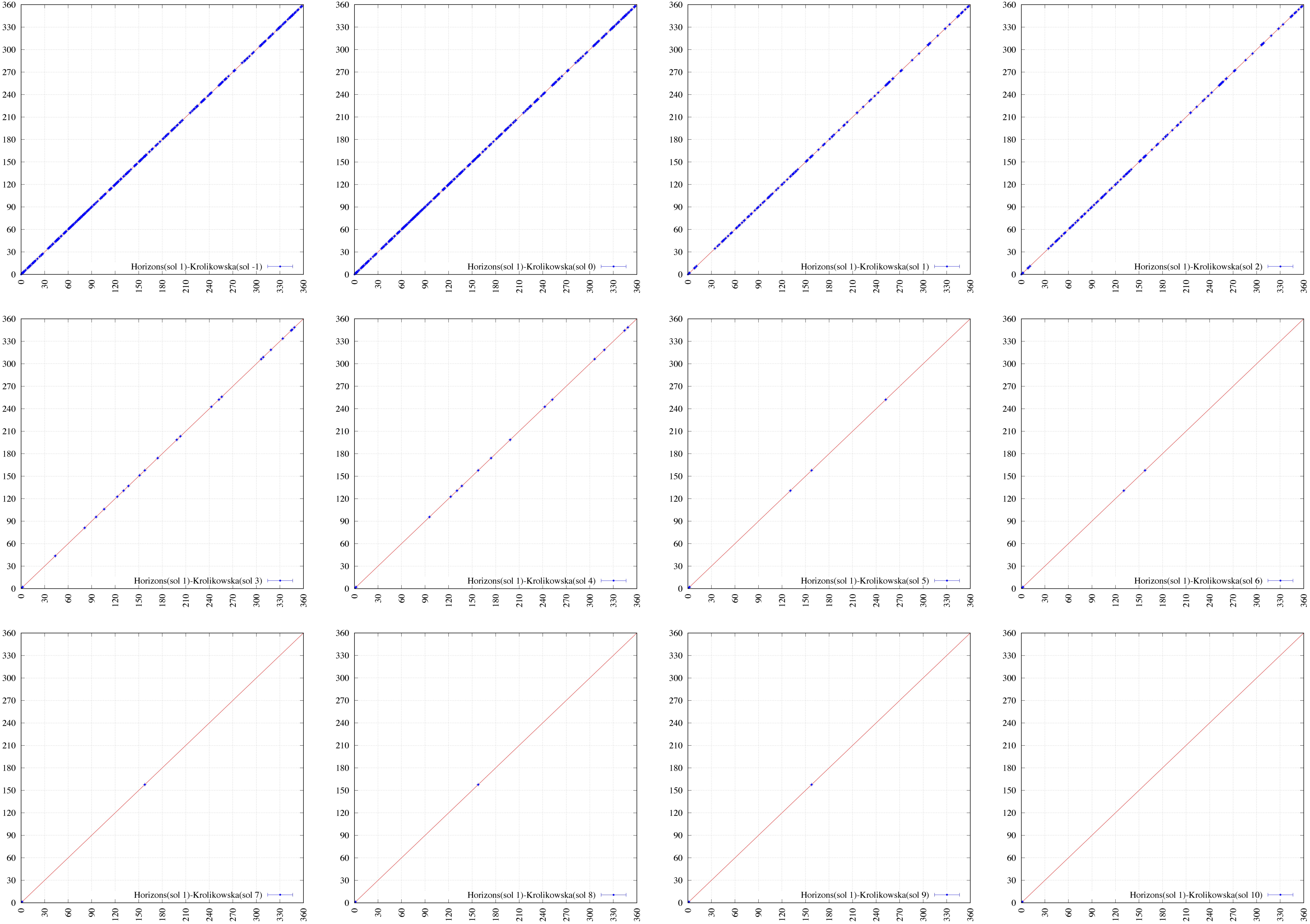


g_{orig}

Krolikowska (the “green” sol) vs. other sols

The unit for both the axe is degree

Krolikowska’ “green” solution was used as the standard for comparison with her solutions 0-11. As we see, they seem quite consistent with each other, and the magnitude of the uncertainties is very small.



g_{orig}

Horizons (w/o err) vs. Krolikowska (0th-11th sols)

The unit for both the axe is degree

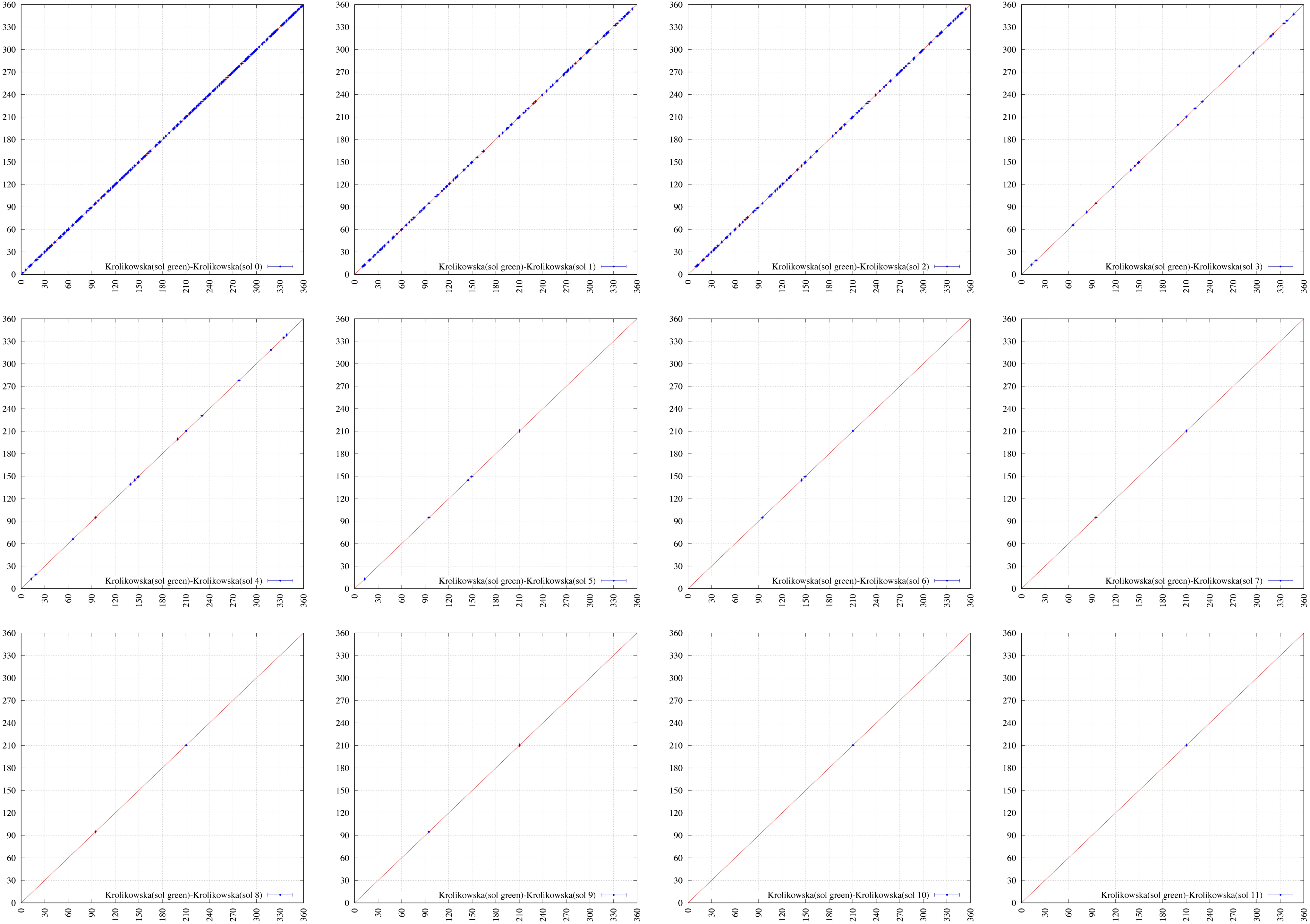
Having the solution given by Horizons as a reference, we plotted Krolikowska's solutions of 12 kind (0-11). As we see, they seem quite consistent, and the magnitude of the uncertainties is very small.

Note that the data points do not have any error bars along the horizontal axis, as we have not calculated them yet through the uncertainties included in the Cartesian coordinates given in the Horizons data.

comparison: longitude of ascending node: $\boldsymbol{h}_{\mathrm{orig}}$

- Krolikowska (the “green” solution) vs. other solutions (0-11)
- Horizons (w/o uncertaintys) vs. Krolikowska (0$^{\mathrm{th}}$-11$^{\mathrm{th}}$ sols)

  - Note that we have not calculated the error propagation of the original longitude of ascending node from the 1σ uncertainties of the Cartesian vector coordinates (x, y, z, v_x, v_y, v_z) that Horizons yields. We will prepare it for our next presentation.
  - Note also that MPC does not provide any information about the original longitude of ascending node.

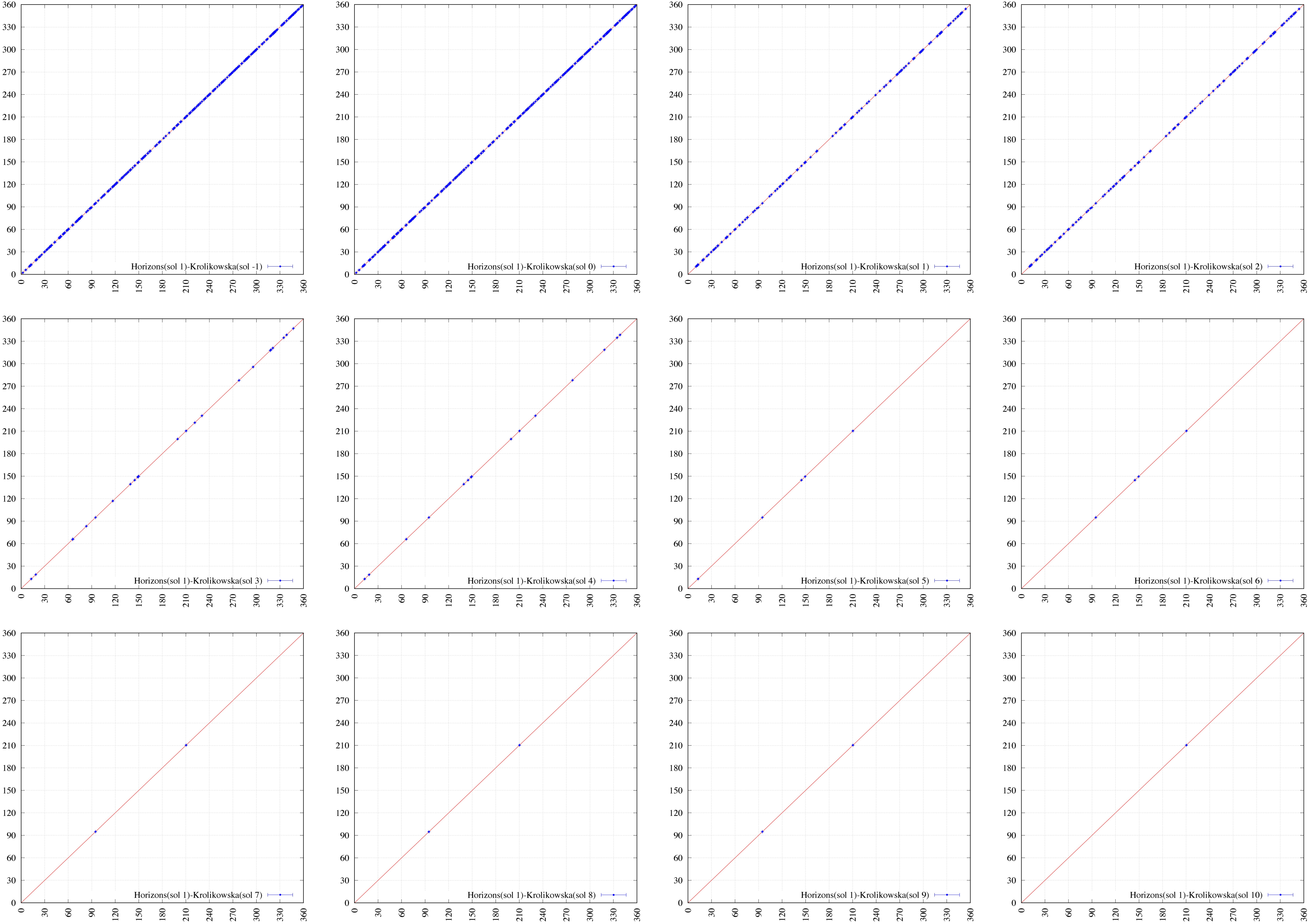


h_{orig}

Krolikowska (the “green” sol) vs. other sols

The unit for both the axe is degree

Krolikowska’ “green” solution was used as the standard for comparison with her solutions 0-11. As we see, they seem quite consistent with each other, and the magnitude of the uncertainties is very small.



h_{orig}

Horizons (w/o err) vs. Krolikowska (0th-11th sols)

The unit for both the axe is degree

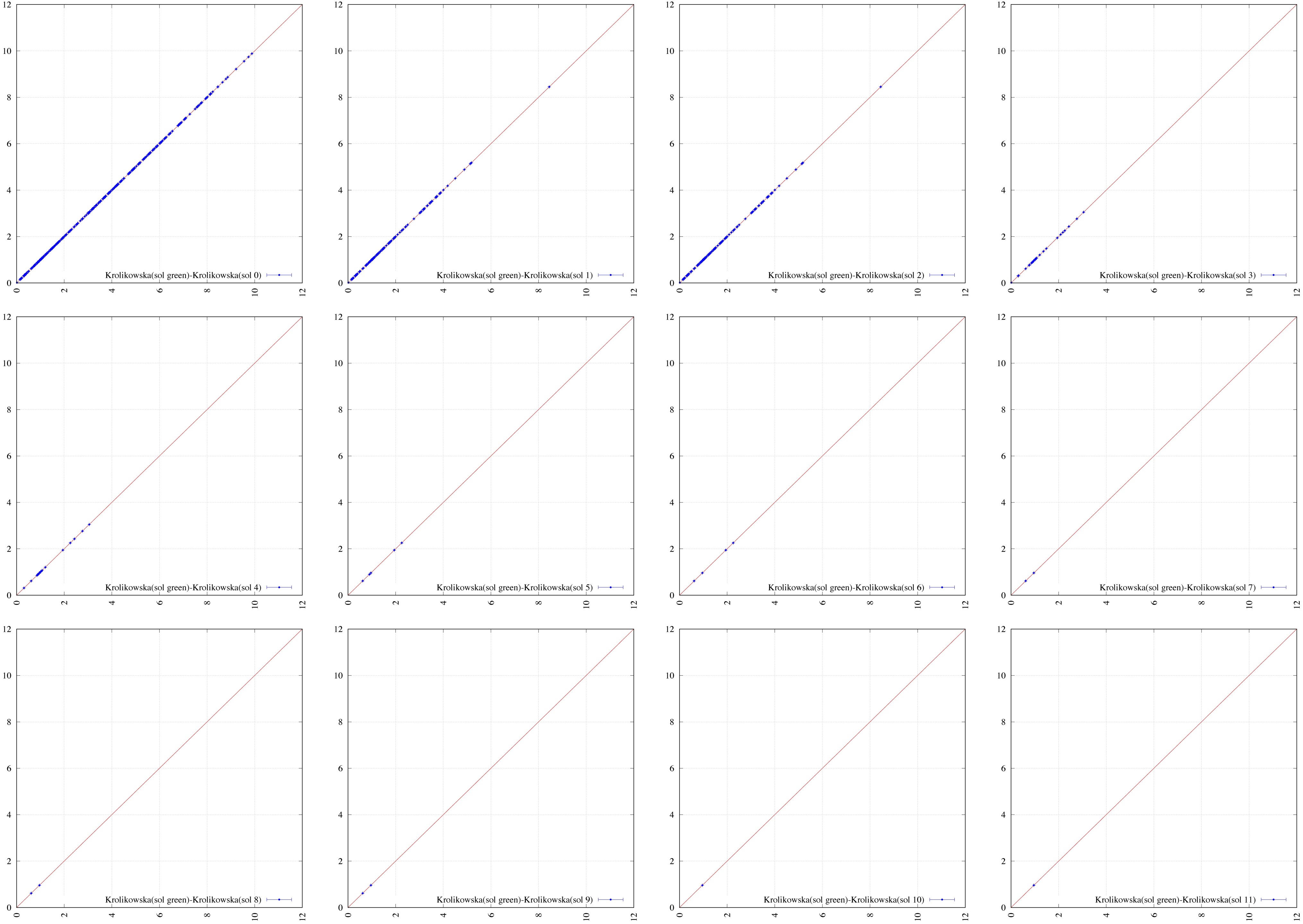
Having the solution given by Horizons as a reference, we plotted Krolikowska's solutions of 12 kind (0-11). As we see, they seem quite consistent, and the magnitude of the uncertainties is very small.

Note that the data points do not have any error bars along the horizontal axis, as we have not calculated them yet through the uncertainties included in the Cartesian coordinates given in the Horizons data.

comparison: perihelion distance: q_{orig}

- Krolikowska (the “green” solution) vs. other solutions (0-11)
- Horizons (w/o uncertaintys) vs. Krolikowska (0^{th}-11^{th} sols)

  - Note that we have not calculated the error propagation of the original perihelion distance from the 1σ uncertainties of the Cartesian vector coordinates (x, y, z, v_x, v_y, v_z) that Horizons yields. We will prepare it for our next presentation.
  - Note also that MPC does not provide any information about the original perihelion distance.

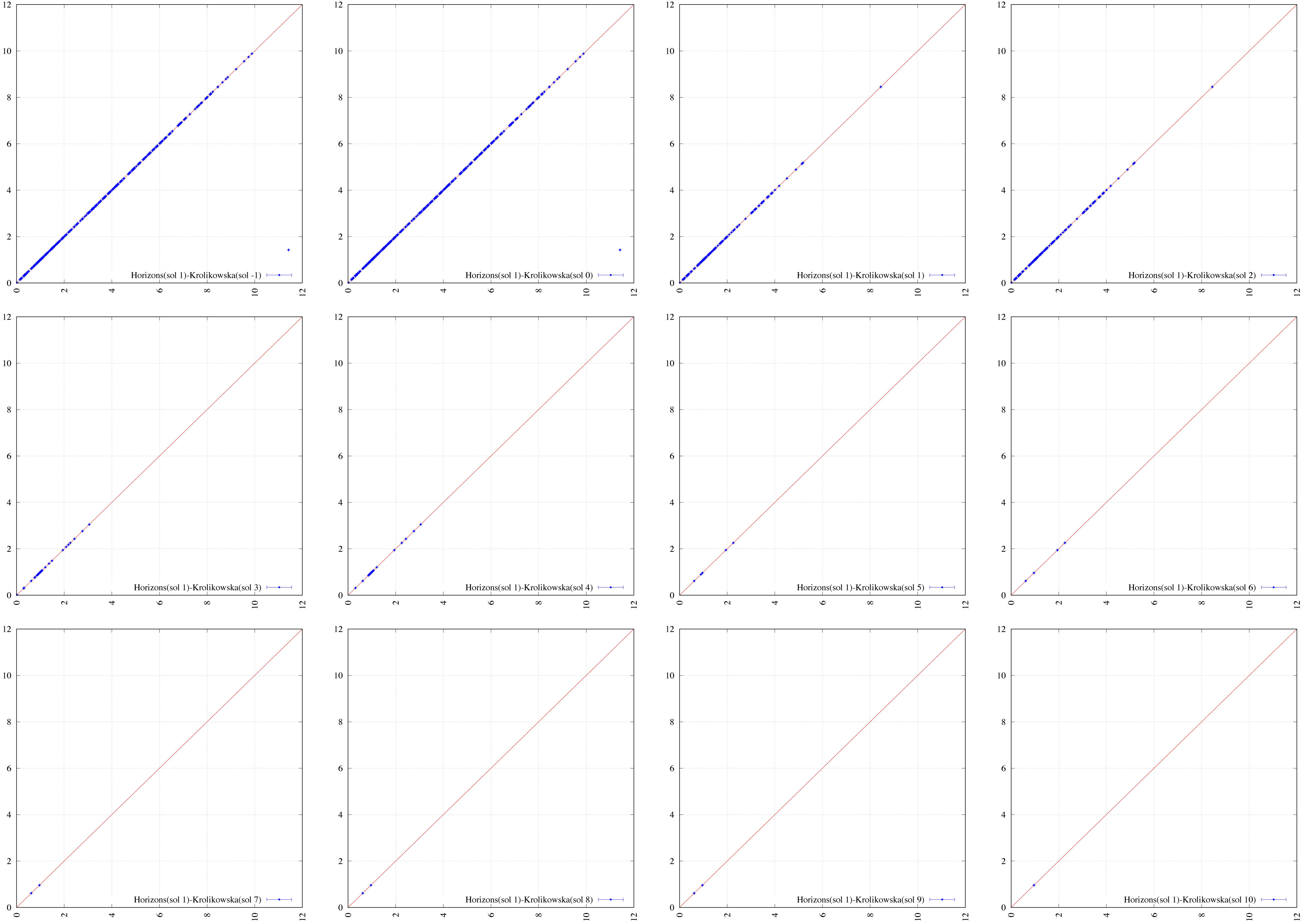


q_{orig}

Krolikowska (the “green” sol) vs. other sols

The unit for both the axe is au

Krolikowska’ “green” solution was used as the standard for comparison with her solutions 0-11. As we see, they seem quite consistent with each other, and the magnitude of the uncertainties is very small.



q_{orig}

Horizons (w/o err) vs. Krolikowska (0th-11th sols)

The unit for both the axe is au

Having the solution given by Horizons as a reference, we plotted Krolikowska's solutions of 12 kind (0-11). As we see, they seem quite consistent, and the magnitude of the uncertainties is very small.

Note that the data points do not have any error bars along the horizontal axis, as we have not calculated them yet through the uncertainties included in the Cartesian coordinates given in the Horizons data.

summary and conclusion

- Krolikowska's cometary catalogue and the MPC ephemeris include multiple orbital solutions for a single comet. In the present study, we illustrated the correlations of the original orbital elements among these orbital solutions, and verified their consistency (or inconsistency). As a result we found that these sets of multiple orbital solutions are largely consistent with each other, particularly for the comets with large semimajor axis such as $|a_{\mathrm{orig}}| > 10000$ au.
- We took the orbital solutions recorded in the Horizons/JPL ephemeris as a reference, and checked out the correlation between this and the original orbital solutions recorded in the Krolikowska catalogue and the MPC ephemeris. As a result we found that these different dataset largely consistent with each other, particularly for the comets with large semimajor axis such as $|a_{\mathrm{orig}}| > 10000$ au.
- The MPC ephemeris and the Horizons ephemeris include a much larger number of cometary samples than the Krolikowska catalogue does. Since it is generally desirable to have as many samples as possible for statistical studies to investigate the current structure and the dynamical origin of Oort Cloud, it will be quite helpful to include not only the cometary data available in the Krolikowska catalogue but also those recorded in the MPC and the Horizons ephemerides.
- Among the original orbital elements that the Horizons ephemeris yields, in this analysis we derived the 1σ uncertainties only for the reciprocal of semimajor axis $(1/a_{\mathrm{orig}})$. This is because the calculation of the 1σ uncertainties is much easier for $1/a_{\mathrm{orig}}$ than for other elements. We will derive uncertainties for other orbital elements (eccentricity, inclination, argument of pericenter, longitude of ascending node, and perihelion distance) via the error propagation formula based on the 1σ uncertainties associated with the cometary position and velocity described in the Cartesian coordinates.

acknowledgment

- The author of this presentation is deeply grateful to Arika Higuchi (University of Occupational and Environmental Health, Japan) and Marc Fouchard (Université de Lille, France) for giving him the opportunity and support to carry out this work.

- NOTE: An equivalent PDF file with the figures with much higher resolution is available from here (~73 MB).