ASTEROID ORBITS WITH GAIA: SIMULATED EXAMPLES

Jenni Virtanen[1], **Karri Muinonen**[1], **Francois Mignard**[2]

[1]Observatory, P.O. Box 14, FI-00014 University of Helsinki, Finland
[2]Observatoire de la Cote d'Azur, Cassiopée, CNRS UMR 6202, Le Mont Gros, BP 4229, 06304 Nice cedex 4, France

ABSTRACT

We apply the theoretical methods and numerical techniques to simulated Gaia observations and discuss the practical requirements for rapid real-time computation of orbits during the active observational phase of Gaia. We pay special attention to the nonlinear phase transition effect from extended orbital distributions to well-constrained ones in the case of high-precision data and illustrate the implications for Gaia with examples.

Key words: Gaia; Asteroids; Near-Earth objects; Asteroid orbit computation; Asteroid identification; Inverse problems.

1. INTRODUCTION

Gaia will carry out a systematic survey of a wide variety of Solar System objects down to magnitude $V = 20$. During the 5-year mission some 500 000 objects will be observed, most of them repeatedly, with an accuracy several orders of magnitude better than with current ground-based surveys. The improved astrometric accuracy will have a major impact on the accuracy of the derived orbits, and in turn on several applications relying on the assessment of orbital uncertainty such as ephemeris prediction, asteroid identification, and collision probability assessment.

We study the evaluation of orbital uncertainties from Gaia observations using 6D statistical orbit computation techniques. The inverse problem of asteroid orbit computation is described in the companion paper (Muinonen et al. 2005), where we provide a sequence of computational techniques applicable from discovery onwards. In this paper we present the application of the various techniques to simulated Gaia observations.

In preliminary simulations for Gaia by Muinonen & Virtanen (2002) (see also Muinonen et al. 2002), a nonlinear collapse was seen in the orbital uncertainties as a function of the improving accuracy of astrometric observations. This phase transition effect can also be recognized in the time evolution of the orbital uncertainty (see, e.g., Virtanen et al. 2004). The existence of such an effect suggests that different computational methods could be used to assess the uncertainties before, at, and after the transition.

We start with the technique of statistical ranging. Close to the discovery moment the observational data of an object is typically exiguous: the number of observations is very small and/or the covered orbital arc is very short. For such data, the covariance matrices computed in the linear approximation (e.g., with the least-squares technique) are known to fail to describe the uncertainties in the orbital parameters. Ranging gives us rigorous means to assess these uncertainties for, e.g., the dynamical classification and collision probability assessment of near-Earth objects at their Gaia discovery moment.

We continue with the novel Monte Carlo technique of phase-space sampling using volumes-of-variation (VOV-technique) for asteroids with moderate time arcs and/or moderate numbers of observations. The nonlinear technique complements the statistical ranging one for exiguous observational data and the least-squares one for extensive observational data. It helps us assess the nonlinear phase transition from extended orbital-element distributions to well-constrained ones. We note that the final Gaia orbit computation requires an iterative solution of the entire inverse problem, including asteroid sizes, shapes, masses as well as accounting for relativistic effects.

We apply the orbital-element sampling techniques to example near-Earth and main-belt objects and discuss the implications for the Gaia asteroid orbit computation task.

2. INITIAL ORBITS

2.1. Phase Transition

We study the phase transition effect of both improving astrometric accuracy and increasing observational time arc by applying our orbit computation scheme to near-Earth and main-belt objects (NEOs, MBOs) with simulated Gaia data. Our preliminary study implied that the occurrence of this nonlinear collapse in the orbital distributions is most likely highly case-sensitive.

For the simulated observations of two near-Earth asteroids 1993 OM_7 and 1998 OX_4 (3 observations covering a time arc of $\sim$ 3 hr; see Muinonen et al. 2002), the nonlinear collapse takes place at the 0.5 and 5 mas level of observational accuracy, respectively. Thus, pinpointing its exact location for each object requires a detailed study. For the time evolution, we break down the object's observational data night by night and apply the different techniques to the data in a sequential manner. For the effect of improving accuracy, we fix the sequence of observational epochs and repeat the orbit computation using different assumptions for the observational noise.

In Figures 1 and 2 we show the phase transition for the simulated Gaia observations of the main-belt asteroid (4) Vesta. For single-epoch Gaia data (4 observations covering 0.4 days), the collapse in the accuracy of the orbital elements occurs for observational noise less than $\sim$ 1 mas. For high-precision data, our studies suggest that the transition for MBOs may take place already at the discovery moment if at least three observations are available, while for current ground-based observations with typical accuracy of some tenths of arcsecond, this transition happens for asteroids with moderate observational arcs and/or numbers of observations (see Virtanen & Muinonen 2004, Muinonen et al. 2004). This is encouraging for the Gaia task of initial orbit computation, because the simulated asteroid observations have turned out to be very sparse in time (for a typical MBO, $\sim$ 70 observations during the 5-yr mission, for NEOs even less), implying that weeks or months may pass before the discovery data is replenished and the orbit improved.

3. REFINED ORBITS

To improve the initial orbits as the observational data of an object becomes more extensive, we compute differentially corrected orbits using the simulated Gaia error model. We again make an application to the simulated observations of (4) Vesta (69 observations from 5 years) to demonstrate the Gaia orbit refinement task.

3.1. Asymptotics

We show the linear trend in orbit refinement as a function of improving accuracy (Figure 3) and increasing Gaia time arc (Figure 4) for Vesta. For the full Gaia arc of 5 years, an order of magnitude improvement in observational accuracy results in similar improvement in the orbital parameters, difference between typical current ground-based accuracy of 0.5 arcsec and Gaia accuracy of mas-level (e.g., $\sim$ 3 mas for $V = 9$ mag MBO) is a factor of 100. The trend in the gradual refinement of the orbit as more Gaia epochs are observed for the asteroid is also close to linear.

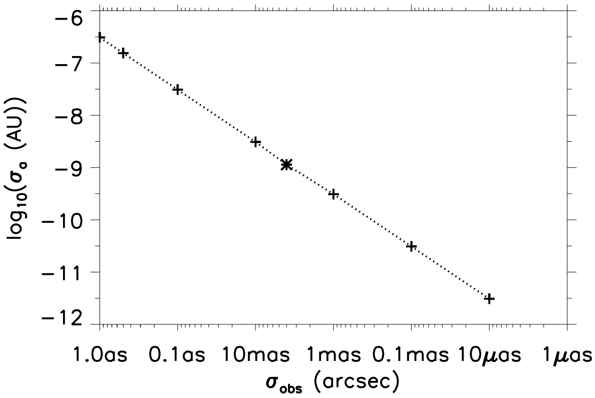

Figure 3. Accuracy of the semimajor axis as a function of the assumed observational accuracy using the full Gaia arc for (4) Vesta. Least squares standard deviations computed with different assumptions for the observational noise (simulated Gaia accuracy marked with a star).

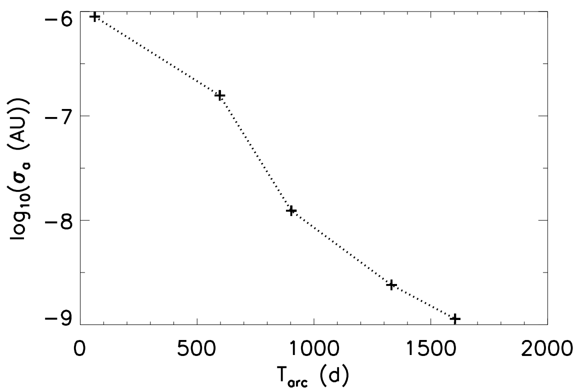

Figure 4. Improving accuracy of the semimajor axis as a function of the increasing Gaia observational arc for (4) Vesta.

4. ORBITS DURING THE GAIA OBSERVING PERIOD

We describe the real-time online processing of Gaia observations. Based on the asteroid orbital data base, we monitor the objects in the Gaia observing window for a rapid assessment of Gaia observations. That is, we maintain a real-time map of the sky by continuous propagation of ephemeris distributions for all known objects. Gaia detections are checked against known objects taking into account the uncertainties in their positions. Based on this identification, the detected objects follow different paths: successful identifications result in refined orbits, while Gaia discoveries lead to new initial orbits to be added in the data base. The data base is thus continuously updated, and at the end of the survey, also the physical properties such as spin states, shapes, and masses of the observed objects should be included and the orbit computation procedure is iterated towards a global solution.

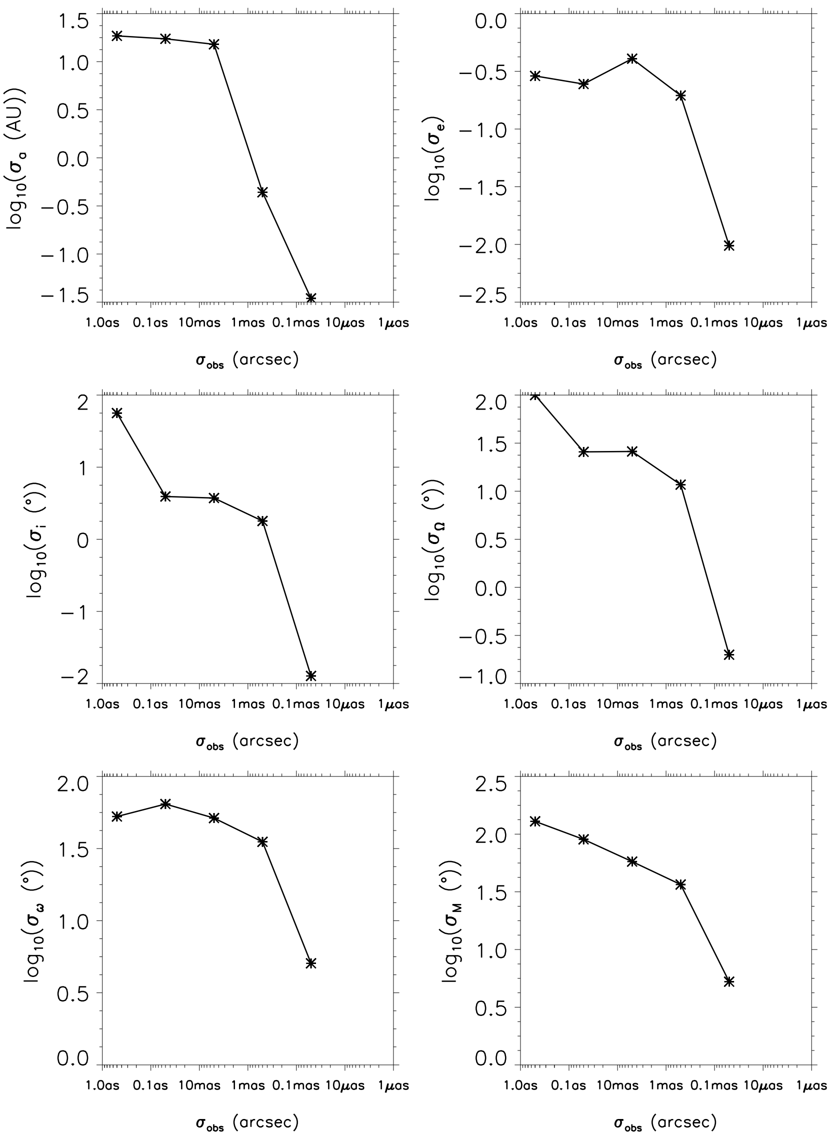

Figure 1. Phase transition in the accuracy of the orbital elements as a function of improving observational accuracy for simulated observations of (4) Vesta. Ranging has been applied to the single-epoch Gaia data (4 observations over 0.4 days) by making different assumptions for the observational noise.

5. CONCLUSION

Making use of simulated Gaia observations, we have demonstrated the potential of modern statistical orbit computation techniques such as Ranging, VOV sampling, as well as the standard least squares technique (linear approximation). The VOV sampling completes the spectrum of 6D statistical orbit computation techniques extending from discovery to long observational arcs, thus also completing the spectrum of orbit computation tools needed for the Gaia mission. The techniques are readily applicable to ephemeris prediction, e.g., sequentially from the discovery to the end of the mission as well as dynamical classification of Gaia discoveries. We can also assess the collision probability for NEOs with high-precision data and study the implications for Gaia discoveries.

ACKNOWLEDGMENTS

The research has been supported by the Finnish Graduate School in Astronomy and Space Physics and by the Academy of Finland.

REFERENCES

Muinonen, K., & Virtanen, J. 2002, Computation of orbits for near-Earth objects from high-precision astrometry. In *Proceedings of the International Workshop on Collaboration and Coordination Among NEO Observers and Orbit Computers* (Kurashiki, October 23-26, 2001, Organized by Japan Spaceguard Association), pp. 105-113

Muinonen, K., Virtanen, J., and Mignard, F. 2002: Ini-

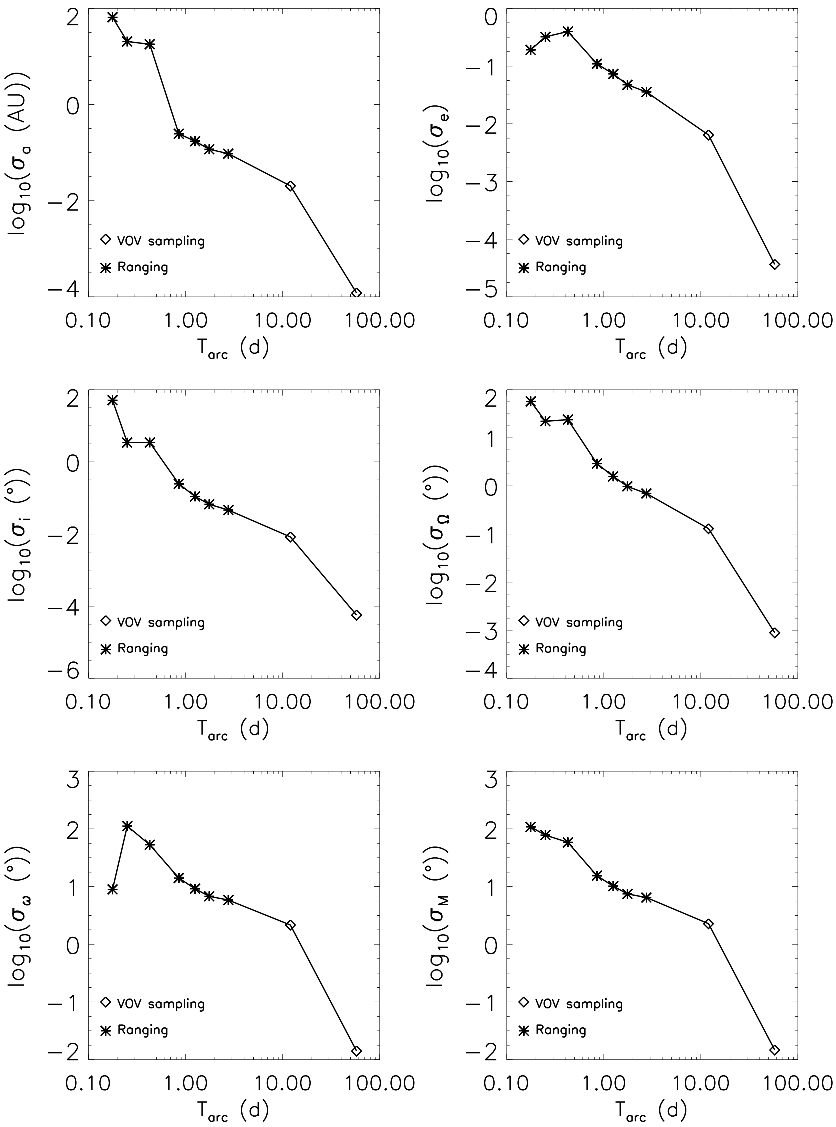

Figure 2. Phase transition in the accuracy of the orbital elements as a function of increasing observational arc for simulated observations of (4) Vesta. Gaia data for 2 months (10 observations) has been broken down to three Gaia observational epochs: 1st day (4 obs.), 12th day (4 obs.) and 58th day (2 obs.). To locate the timing of the collapse between the first and second Gaia epoch, we propagated the 4 observations from the second epoch backwards, simulating the situation where the follow-up epoch would have been obtained earlier.

tial orbits for near-Earth objects from high-precision astrometry. *Extended Abstracts from the NASA Workshop on the Scientific Requirements for Mitigation of Hazardous Comets and Asteroids* (E. Asphaug and N. Samarasinha, eds.), 75–77

Muinonen K., Virtanen J., Granvik M, and Laakso T., 2004, Asteroid orbits using phase-space volumes of variation, MNRAS, to be submitted

Muinonen K., Virtanen J., Granvik M, and Laakso T., 2005, ESA SP-576, this volume

Virtanen J., and Muinonen K., 2004, Time evolution of orbital uncertainties at discovery for the impactor candidate 2004 AS_1, Icarus, submitted.

Virtanen J., Muinonen K., Granvik M., and Laakso T., 2004, Collision orbits and phase transition for 2004 AS_1 at discovery, in Dynamics of Populations of Planetary Systems, Proceedings IAU Colloquium No. 197, (Z. Knezević and A. Milani, Eds.), submitted