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Studies of asteroids with exiguous astrometry from synoptic surveys

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Cover picture: The averaged residence-time distribution of Earth' temporarily-captured orbiters, projected onto the ecliptic in the Sun-Earth co-rotating frame. The eye-shaped contour is the trajectory of "the moon of maximum lunation" from Hill (1878), explaining the excess of TCOs in quadratures (from Paper I).

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Abstract

Astrometry, i.e., the study of positions of stellar-appearing heavenly bodies, is the basis for all astronomical research. Each generation of new astronomical surveys delivers new insights into the structure of the Universe, including our Solar System. Small bodies of the Solar System, asteroids and comets, are the populations which reveal the initial conditions, overall structure, and previous processes shaping the Solar System.

With the incremental development of the impressive survey programmes, certain types of objects will always be on the threshold of discoveries. Therefore, only a small number of data for these objects will ever be available. In this thesis, two such Solar System populations are investigated: Earth's temporary natural satellites, and asteroids discovered by the Gaia mission.

The statistical properties and steady-state population of two sub-populations of Earth's natural satellites, temporarily-captured orbiters and flybys, are assessed. The challenges for detection and prospects for future investigation of Earth's natural satellites are discussed. Also, the detectability of Earth's temporarily-captured orbiters with the upcoming Large Synoptic Survey Telescope is investigated, raising the importance of dedicated treatment for small fast-moving objects in the processing.

One of the many fields of astronomy where ESAs Gaia mission makes an important contribution is the discovery of newly discovered asteroids. Candidates for newly discovered asteroids are processed daily and distributed to follow-up observers. A new statistical orbital inversion method, random-walk ranging, is developed. Additionally, the method to improve follow-up predictions by lowering the effect of systematic errors is introduced.

This thesis gives an overview of the phenomenon of the temporary capture of asteroids by planets. The statistical ranging-based orbital inversion methods are discussed. The advancements in the fields of stellar and asteroid astronomy over the ages, and respective breakthroughs in the relevant fields of astronomy are assessed.

J'avais ainsi appris une seconde chose très importante : C'est que sa planète d'origine était à peine plu grande qu'une maison!
[...]
J'ai de sérieuses raisons de croire que la planète d'où venait le petit prince est l'astéroïde B 612. Cet astéroïde n'a été aperçu qu'une fois au télescope, en 1909, par un astronome turc.

Antoine de Saint-Exupéry,
Le Petit Prince, 1943.

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One particularly unforgettable experience has been spending a year as a student support astronomer at the Nordic Optical Telescope on the beautiful island of La Palma. Learning observational astronomy and getting insights into the neighbouring fields was indeed invaluable, and although this work has only exiguous observations, I am certain that the obtained knowledge will be beneficial in the nearest future.

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Acronyms and abbreviations used in the text

ATLAS	Asteroid Terrestrial-impact Last Alert System
CCD	Charge-coupled device
CSS	Catalina Sky Survey
Dec.	Declination
ESA	European Space Agency
Hipparcos	High Precision Parallax Collecting Satellite
JWST	James Webb Space Telescope
LINEAR	Lincoln Near-Earth Asteroid Research
LONEOS	Lowell Observatory Near Earth Object Survey
LSST	Large Synoptic Survey Telescope
MCMC	Markov chain Monte Carlo
NEAT	Near-Earth Asteroid Tracking (Programme)
NEO	Near-Earth object
NEOWISE	Near-Earth object Wide-field Infrared Survey Explorer
NES	Natural Earth's satellite
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
p.d.f.	Probability density function
R.A.	Right ascension
SDSS	Sloan Digital Sky Survey
SPHEREx	Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer
TCF	Temporarily-captured flyby
TCO	Temporarily-captured orbiter
TNO	Trans-Neptunian object
UCAC	United States Naval Observatory CCD Astrograph Catalog
USNO	United States Naval Observatory (Catalogue)
ZTF	Zwicky Transient Facility

Symbols and units

L_1, L_2, L_4, L_5	First, second, fourth and fifth Lagrange point

$a, a_\odot, a_\oplus$	Semimajor axis, heliocentric, geocentric
$e, e_\odot, e_\oplus$	Eccentricity, heliocentric, geocentric
$i, i_\odot, i_\oplus$	Inclination, heliocentric, geocentric
$\Omega, \Omega_\odot, \Omega_\oplus$	Longitude of the ascending node, heliocentric, geocentric
$\omega, \omega_\odot, \omega_\oplus$	Argument of perihelion, heliocentric, geocentric
$M, M_\odot, M_\oplus$	Mean anomaly, heliocentric, geocentric

$\mathbf{P}$	Vector of six orbital elements
$\mathit{\Psi}$	Vector of sky positions
$\boldsymbol{\Psi}(\mathbf{P})$	Computed topocentric light-time corrected positions
ϵ	Random error
υ	Systematic error
p	Probability density
Λ	Covariance matrix for observational errors
σ	Standard deviation

$\alpha, \dot{\alpha}$	Right ascension, right ascension motion
$\delta, \dot{\delta}$	Declination, declination motion
ρ	Topocentric range
H	Absolute magnitude
V	Apparent magnitude

List of publications

Paper I: Fedorets, G., Granvik, M. & Jedicke, R. (2017). Orbit and size distributions for asteroids temporarily captured by the Earth-Moon system. *Icarus* **285** 83 – 94.

Paper II: Jedicke, R., Bolin, B. T., Bottke, W. F., Chyba, M., **Fedorets, G.**, Granvik, M., Jones, L. & Urrutxua, H. (2018). Earth's Minimoons: Opportunities for Science and Technology. *Frontiers in Astronomy and Space Sciences* **5** A13.

Paper III: Fedorets, G., Granvik, M., Jones, R. L., Jurić, M. & Jedicke, R. (2019). Discovering Earth's transient moons with the Large Synoptic Survey Telescope. *Submitted to Icarus.*

Paper IV: Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., Brown A. G. A. and 621 co-authors, including **Fedorets, G.** (2016). The Gaia mission. *Astronomy & Astrophysics* **595** A1.

Paper V: Muinonen, K., **Fedorets, G.**, Pentikäinen, H., Pieniluoma, T., Oszkiewicz, D., Granvik, M., Virtanen, J., Tanga, P., Mignard, F., Berthier, J., Dell'Oro, A., Carry, B. & Thuillot, W. (2016). Asteroid orbits with Gaia astrometry using random-walk statistical ranging. *Planetary and Space Science* **123** 95 – 100.

Paper VI: Tanga, P., Mignard, F., Dell'Oro, A., Muinonen, K., Pauwels, T., Thuillot, W., Berthier, J., Cellino, A., Hestroffer, D., Petit, J.-M., Carry, B., David, P., Delbò, M., **Fedorets, G.**, Galluccio, L., Granvik, M., Ordenovic, C. & Pentikäinen, H. (2016). The daily processing of asteroid observations by Gaia. *Planetary and Space Science* **123** 87 – 94.

Paper VII: Fedorets, G., Muinonen, K., Pauwels, T., Granvik, M., Tanga, P., Virtanen, J., Berthier, J., Carry, B., David, P., Dell'Oro, A., Mignard, F., Petit, J.-M., Spoto, F. & Thuillot, W. (2018). Optimizing asteroid orbit computation for Gaia with normal points. *Astronomy & Astrophysics* **620** A101.

Contents

1 Introduction

Astrometry, i.e. the measurement of positions of objects with stellar appearance, is the oldest branch of astronomy. Throughout the ages, astrometry has attained the prime technology of its time, and has served as a source for major advances in natural sciences, such as heliocentrism, Newtonian mechanics, and the structure of the Universe. In the last 30 years, with the immersion of spaceborne astrometric facilities, fast advancement in detector technologies, and efficient automatic processing of observations, the field of astrometry has taken a significant leap forward.

The progress in observations of asteroids has followed general advancements in astrometry. A special interest in discovering new asteroids has been the realisation of their impact threat with the Earth. The largest recorded event in modern history was the Tunguska event in 1908 (Kulik 1922). The global threat posed by asteroids was revealed with the impact nature of the mass extinction event at the K-T boundary (Chixculub event, Alvarez et al. 1980). A notable reminder of the asteroid threat came in the form of the Chelyabinsk event in 2013 (Popova et al. 2013). It shifted the focus of the threat assessment from rare global catastrophies triggered by kilometre-sized objects towards more frequent local threats posed by decametre-sized objects. These events have put the focus of asteroid astrometry on the detection of near-Earth objects, although numerous other asteroids, mostly in the main belt, have been discovered at the same time. The most notable political decision regarding the asteroid threat was made by the Congress of the United States of America. The initial goal was to discover 90% of potentially-hazardous asteroids with the diameter higher than 1 km. After this goal has been reached (Harris & D'Abramo 2015), it was extended to the size of 140 m to be completed by 2030.

The impact threat has been the main driver for dedicated asteroid observations. This has, in part, led to the disproportionately high amount of astrometric data over any other data types. Although brightness information has always been reported, multi-colour photometry has been only lately included in some asteroid-dedicated surveys. Complementary observations from non-dedicated surveys have helped in getting some compositional information on asteroids.

The enhanced capabilities of automated data processing have mended fences between different branches of observational astronomy. Surveys adapting a synoptic approach to astronomical objects have come along with the traditional dedicated surveys. Due to the consolidation of efforts, the synoptic surveys often have advanced capabilities in terms of accuracy, field of view, astrometric depth, or a combination of some of the above. Notable examples of contemporary synoptic surveys are ESA's Gaia mission and the upcoming Large Synoptic Survey Telescope (LSST).

In terms of astrometry, the term exiguous or sparse data can be defined precisely. The term refers to the amount of astrometric data not sufficient enough to produce a Gaussian p.d.f. for a resulting set of orbits from orbital inversion. The subsequent generations of astronomical surveys will continuously unveil new populations of Solar System objects on the edge of detectability. For these objects the given survey will not be able to provide a sufficient amount of data for a well-defined orbit. This is the case for the types of objects observed with synoptic surveys which are investigated in this thesis: newly discovered asteroids of Gaia, and Earth's temporary captured satellites with LSST. Both populations are examples of objects which are observed with the respective surveys only over a short period of time after the discoveries. Unlike many other asteroids, both types of objects can usually be observed only over a period of a few days until they are out of reach of the observer for different reasons. In these cases, the future detections of the asteroid depends only on the follow-up observers.

Earth's temporarily-captured satellites are small, and therefore difficult to detect – the largest of the temporarily-captured objects typically experience a brightening surge which barely allows them to be detected by the largest of upcoming astrometric surveys. In this thesis, the population of these objects is examined and their detectability is assessed.

The continuous scanning law of Gaia combined with the sky motion of asteroids limits acquiring astrometric positions of asteroids to a couple of days until the next possibility. The thesis introduces the pipeline for detecting new objects, a new method for orbit determination, and the means to reduce the role of observational statistical error for follow-up orbit determination.

This thesis consists of the overview part followed by seven peer-reviewed publications. The overview part is organised as follows. In Chapter 2 the small Solar System bodies are introduced, and their significance in the broad context of planetary science is assessed. An emphasis is given on the phenomenon of the temporary capture of asteroids by planets, and especially, the captures by Earth. In Chapter 3, the orbital inversion problem of asteroids is reviewed. Special attention is given to the methods developed for the Gaia mission. In Chapter 4, an overview of advancements from various survey programmes is given, with a special focus on the past, present and future advancements by various surveys studying asteroids. In Chapter 5, the summary of publications is given, and the input of the author for each article is described. The thesis is summarized in Chapter 6.

2 Small Solar System bodies

2.1 Brief overview of small Solar System bodies

The population of small Solar System bodies consists of asteroids (from Greek ὰστϵροϵιδής - “star-like”) and comets (from Greek *κομήτης* - “wearing long hair”). In general, the difference stems from the distance of their formation region from the Sun. Asteroids, formed inside the orbit of Jupiter, are considered collisionally-evolved remnants of planetesimals and protoplanets of the inner Solar System. Comets are thought to be the remains of planetesimals from the outer parts of the Solar System (Brownlee 2014).

The common distinction between asteroids and comets has been the visible dust and gas activity of comets, which is generally lacking from asteroids. However, the discoveries of active asteroids as well as Manx (i.e. inactive objects on cometary near-parabolic orbits) and depleted comets has raised the understanding that the population of small Solar System bodies is a compositional and dynamical continuum of objects of different sizes. For simplicity, the term “asteroid” will be used from now on instead of the cumbersome term “small Solar System object”.

The oldest solidified material found in the Solar System are the calcium-aluminium rich inclusions found in meteorites radio-dated to the age of 4.5682 billion years (Bouvier & Wadhwa 2010). The solidification of the oldest material was followed by the rapid chain of events on the timescale of 10 million years, which eventually resulted in the formation of planetesimals and subsequently, giant planets (Chambers 2014). Asteroids are a remaining source of original material from the era of the formation of the Solar System. The versatile population of asteroids provides a natural dynamical and geological laboratory and an important source of information about the formation and evolution of the Solar System.

There is no formal lower limit for the size of an asteroid, although some researchers propose one metre as a boundary to distinguish between asteroids and meteoroids. The smallest discovered asteroid has magnitude $H = 35.9$, which with the standard albedo value of 0.15 translates to a diameter of 25 cm (Lue et al. 2019).

The upper size limit for asteroids has been coined to require the failure of achieving the state of hydrostatic equilibrium (IAU resolutions 5A and 6A, XXVI general meeting, 2006). Thus, formally, the largest object in the main asteroid belt, (1) Ceres, is a dwarf planet, whereas the second largest object, (4) Vesta, is an asteroid.

The dynamical evolution of the Solar System has spread the asteroids throughout. The major stable remnant population of asteroids in the Solar System is situated in the main asteroid belt between Mars and Jupiter. A large part of asteroids is situated around Jupiter's L_4 and L_5 regions as Jupiter Trojans. A significant population of small Solar System bodies, including the cold classical belt and the scattered disk, lies beyond the orbit of Neptune, comprising the population of transneptunian objects (TNOs). Other populations, such as near-Earth objects and Centaurs are transient populations, and are discussed in Sect. 2.2.

Combining the orbital and size-frequency distributions of various asteroid populations with their observed physical properties pose constraints on various phenomena shaping the Solar System. By extending the analysis into the past, not only do the different events in the history of the Solar System become unveiled, but also constraints on the initial conditions and processes shaping its formation are set. As an example, the inhomogeneity of the composition of the main asteroid belt as well as the colours of Jupiter's Trojans and the separated colours of the two distinct TNO populations are all characteristics which need description. All these phenomena can be explained at the same time by the 2:1 mean-motion resonance event between Jupiter and Saturn hundreds of millions of years after the formation of the Solar System (Nice model, Tsiganis et al. 2005, Gomes et al. 2005, Morbidelli et al. 2005). An overview on the current state of knowledge about the construction of the Solar System is given by Raymond et al. (2019).

Traditionally, the bulk of asteroid observations has included mainly astrometric positions. Typically, when the object is discovered, several astrometric positions are obtained. Follow-up observations are always required, and a build-up of astronomical data identifies the interesting subjects for more thorough investigation. The majority of physical characterisation data for asteroids comes from traditional astronomical methods (photometry, spectrometry, polarimetry). The beginning of the space flight era has also enabled in situ exploration of Solar System objects, which allowed high-resolution characterisation of selected bodies of the Solar System. The domain of asteroid science, and more broadly, planetary science, has evolved into an inter-disciplinary field combining astronomy, physics, chemistry, geology, geophysics, and meteorology. Behind the results from impressive space missions, geologically characterising single Solar System bodies, the astronomical approach remains necessary for the overwhelming majority of asteroids.

The pristine early Solar System material is also delivered to Earth in the form of meteorites. The asteroid-meteorite connection is in the active phase of being established with in situ and sample return missions such as Hayabusa to the S-type asteroid (25143) Itokawa; Rosetta to comet 67P/Churyumov-Gerasimenko; Hayabusa2 to the C-type asteroid asteroid (162173) Ryugu, and OSIRIS-REx to the C-type asteroid (101955) Bennu (for an overview, see e.g. Binzel et al. 2015). A comprehensive understanding of the physical properties of asteroids requires a combination of ground-based observations, meteorite studies and in situ and sample return missions.

The number of discovered asteroids has significantly increased since the 1990s. It has become increasingly important to ensure the effectiveness of follow-up astrometric observations by improving the quality of ephemeris predictions. In case of NEOs, constraining the orbital parameters is also important for assessing their impact hazard with the Earth. Due to mutual gravitational perturbations of asteroids, their close encounters with planets, and non-gravitational forces such as the Yarkovsky force (e.g. Öpik 1951, Bottke et al. 2006), the assessment of the impact hazard is a continuous process since the orbits of asteroids and their impact risk need to be constantly updated with new observations.

2.2 Populations of transient small Solar System bodies

From an observational point of view, all small Solar System bodies may be considered transients. The stability of asteroid populations is often considered from a dynamical perspective. Dynamically stable small body populations of the Solar System contain main-belt asteroids (MBAs), including Hungarias and Hildas, Trojans of Jupiter and other planets, trans-Neptunian objects, and the hypothesized Öpik-Oort cloud. Dynamically stable populations are sources for transient populations which are populated with objects ejected to various unstable orbits.

Objects in transient populations are of particular interest for research of physical properties of asteroids. Although the dynamical scattering of asteroids occurs both towards and away from the Sun, the detectable transient objects are essentially members of distant populations brought to more favourable observing conditions. Investigating new dynamically fresh objects also implies finding unaltered surfaces from long distances before they become susceptible to sublimation and space weathering.

The planets of the inner Solar System have long-term stability with 98% probability (Laskar & Gastineau 2009). Therefore, large cataclysms affecting the current structure of the Solar System and the overall structure of its asteroid populations are foreseen only in the unlikely event of the traverse of a large interstellar rogue planet into the Solar System. Meanwhile, the dynamical evolution of stable populations continues on a smaller scale up to this day. Most notable transient populations of small Solar System objects are near-Earth objects (NEOs), Centaurs, and short- and long-period comets.

The NEO population is a transient population of asteroids in the inner Solar System. It is constantly replenished from the main belt when asteroids are ejected through Kirkwood gaps (which correspond to the areas where mean-motion resonances with giant planets occur) and secular resonance zones (Granvik et al. 2017). The path of an asteroid to these areas of dynamical instability typically begins with mutual collisions. A collision results in a collection of objects of various sizes with a mutual origin. Such collection is called an asteroid family. Smaller objects in the new asteroid family are more vulnerable to thermal Yarkovsky forces (Bottke et al. 2002a), which are inversely proportional to the size of the object (Vokrouhlický et al. 2015). For the long term effect on asteroids' semimajor axes, the weakness of the Yarkovsky force is compensated by its perpetuality. Under a long term influence of the Yarkovsky force, the semimajor axis of the asteroid is altered, depending on their size and rotational direction. Eventually, some asteroids reach a resonance and are ejected into the NEO region. There, through a series of close encounters with planets, asteroids eventually impact with one of the inner Solar System planets, or, in most cases, the Sun. Alternatively, they disintegrate directly, if they have close approaches to the Sun (Granvik et al. 2016).

In the outer Solar System, a notable asteroid transient population is called Centaurs, which are objects in a transitional phase from the TNO population inwards. Their semimajor axes lie between those of Jupiter and Neptune, and their orbits are not stable, but rather dominated by close encounters with giant planets. In the case of Jupiter, the close encounters may even lead to an ejection from the Solar System, but also to the ingestion into the inner Solar System, where they are generally expected to sustain cometary activity. Not much is known about their surface composition, but they are believed to resemble dormant comets.

Centaurs may eventually evolve into short-period comets. The perihelion of these comets lies in the inner Solar System, while their aphelion is just within the reach of one of the giant planets. The definition of short-period comets is that their orbital period does not exceed 200 years (e.g. Levison & Duncan 1994). Consequently, the common feature of short-period comets is that their eccentricity is not near-parabolic, which is the case for the majority of comets. The short-period comets are sub-divided into families, which usually derive their name from the planet close to which the aphelion of the comet lies. As an exception, there are also Halley- and Encke-family comets, names after the prominent comets the orbits of which do not follow the aforementioned rule. Long-period comets exceed the conventional orbital period of 200 years, have near-parabolic eccentricities, and originate from direct perturbations in the trans-Neptunian scattered disk and even in the Öpik-Oort cloud.

2.3 Temporary captures in general

Temporary captures of asteroids by planets are special occurrences in transient populations. Their duration as a population is short compared to those of other transient populations, being on the order of months and years. Other transient populations typically have lifetimes of at least thousands of years. During the capture, the asteroid comes under dominating gravitational influence of the planet. Several different definitions exist for the phenomenon of temporary capture. For practical reasons, the definition proposed in Paper I is used in this thesis. Combining the approaches of Kary & Dones (1996) and Emel'yanenko (2015), the definitions for temporary captures is as follows:

- A temporarily-captured orbiter (TCO) is an object which appears on a geocentric elliptic orbit within 3 Hill radii, comes within 1 Hill radius, and makes at least one revolution around the planet during the capture.
- A temporarily-captured flyby (TCF) is otherwise similar to the TCO, except that it fails to make a complete revolution around the planet.
- Together, TCOs and TCFs comprise the population of natural Earth's satellites (NESes).

The phenomenon of temporary capture can perhaps be best understood in the framework of the classical restricted circular three-body problem (see Fig. 1), containing a central star, a planet and a massless body, which is a valid approximation for an asteroid (e.g. Danby 1992). If the orbital elements of the asteroid are close to those of a planet, and the value of the Jacobi integral of the asteroid is appropriate, then the temporary capture is possible. The value of the Jacobi integral needs to allow the circum-planetary permitted region to be connected to the circum-stellar permitted region through the L_1 region, and possibly also to the general permitted region through the L_2 region. The Jacobi integral is a key parameter for temporary capture – for example, in terms of Earth, the range of Jacobi integrals permitting the temporary capture is less than 0.004 (Granvik et al. 2012).

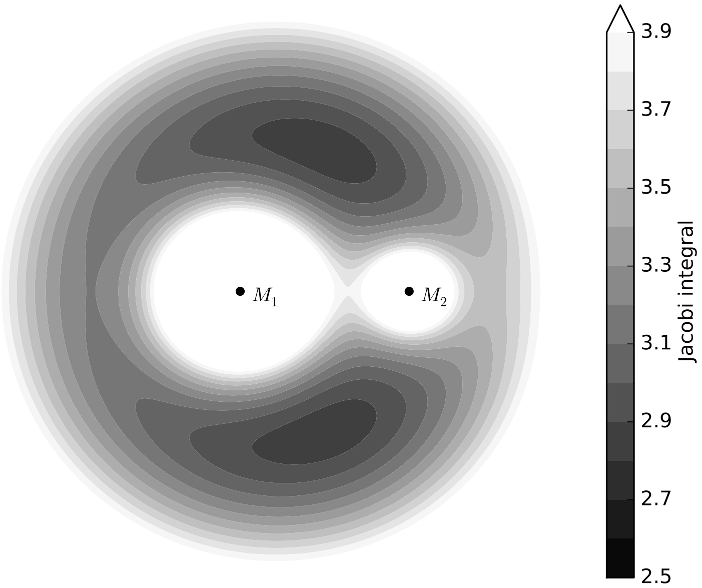

Figure 1: The depiction of zero velocity curves for various values of the Jacobi integral in the restricted circular three-body problem. The permitted regions of movement of the massless asteroid depend on the value of the Jacobi integral. Here, M_1 represents the star, and M_2 the planet. Image is produced with adapted code from https://github.com/norabolig/threeBodyCJ

A capture of an outside object, in addition to in situ formation and catastrophic collisions, is a means to create a gravitationally-bound multiple-body system. The methods for permanent captures in planetary systems include reaccumulation after a giant impact (the case of the Moon, Canup & Asphaug 2001), frictional drag in the early stages of the evolution of the Solar System (Everhart 1979), or capture during close encounter by another massive body (Nesvorný et al. 2007). The current understanding is that irregular satellites of planets, such as Neptune's Triton, are objects which became captured during a planetary encounter with another massive body. Without such an encounter occurring, the irregular satellites would have eventually escaped.

When the Solar System became emptied of asteroids in the vicinity of the planets, the semimajor axes of the latter became dynamically stabilised. Thus, the sources of additional impulses during the capture period, and consequently, the possibilities for permanent captures of asteroids have been effectively depleted. Therefore, permanent captures of asteroids in the current configuration of the Solar System are not possible (Everhart 1979, Astakhov et al. 2003). Temporary captures, however, still may occur on a regular basis. Spending non-negligible time in a planet's Hill sphere on an elliptic planetocentric orbit in the framework of the elliptic restricted three-body problem is possible for all planets (Bailey 1972). In particular, the phenomenon of temporary capture has been extensively studied for comets and Jupiter. The orbital interaction of comets with Jupiter is important for understanding the source for short-period comets and the overall transition of bodies inwards from the outer Solar System.

One possible outcome of close encounters of long-period comets with Jupiter is their transition to Jupiter-family comets. Kazimirchak-Polonskaya (1972) showed that during such close encounters, the temporary capture mechanism significantly alters the orbit of comets, as with comet 39P/Oterma between 1936 and 1938. Temporary captures of comets by Jupiter appear to actually be rather common and happen for comets on tangential approaches to Jupiter (Carusi & Valsecchi 1979). Seven out of 97 periodic comets known in 1972 (i.e. comets 31P/Schwassmann-Wachmann 2, 36P/Whipple, 39P/Oterma, 61P/Shajn-Schaldach, 65P/Gunn, 82P/Gehrels 3 and 99P/Kowal) have had elliptic jovicentric elements during close approaches with Jupiter over the last 250 years (Carusi & Valsecchi 1981). Later, comets 111P/Helin-Roman-Crockett (Tancredi et al. 1990) and 147P/Kushida-Muramatsu (Ohtsuka et al. 2008) have been added to the group of periodic comets that experienced temporary captures with Jupiter. As a conclusion, the temporary capture phenomenon plays a notable role in the transfer of cometary bodies from transient Centaur orbits to short-period Jupiter-family comet orbits.

Perhaps the most famous temporarily-captured object was comet D/1993 F2 Shoemaker-Levy 9. Probably captured into a jovicentric orbit in the late 1920s (Chodas & Yeomans 1996), it came within Jupiter's Roche limit, disintegrated into a number of fragments, and eventually impacted Jupiter in July 1994. The impact on the one hand demonstrated the important role which Jupiter performs in shielding the inner Solar System from inbound comets, and, on the other hand, acted as another reminder of the asteroid impact hazard.

Temporary captures should not be confused with asteroids experiencing the co-orbital motion with the planet. In a Sun-planet co-rotational frame, there are three different modes of co-orbital motion (Mikkola & Innanen 1997, Brasser et al. 2004). First, the tadpole orbits, which occur when asteroids librate around Lagrangian points L_4 and L_5, resulting in Trojan populations. Second, the horseshoe orbits, where asteroids librate almost throughout the entire span of Earth's orbit. Third, the quasi-satellites, such as (469219) Kamo'oalewa (de la Fuente Marcos & de la Fuente Marcos 2016), which appear to rotate around the planet in a retrograde manner in the co-rotational frame. They are, however, not gravitationally bound to the planet, and do not appear within the Hill sphere of the planet. Asteroids on co-orbital modes often interchange these modes from one to another on the time scale of hundreds to thousands of years. In terms of the restricted circular three-body problem, quasi-satellites and NESes have different Jacobi integrals.

The main difference between various modes of temporary captures and co-orbitals is that the temporary captures are gravitationally bound to the planet, appearing in the planet's Hill sphere, whereas the co-orbitals are not. Co-orbitals are more distant, and may at times appear behind the Sun. Also, co-orbitals have semimajor axes and orbital periods close to those of the planet, but their eccentricities tend to be higher than for temporary captures, the eccentricities of which are close to zero.

2.4 Earth's temporary captures

While the phenomenon of temporary captures of asteroids has been known for a long time, it was not until the work of Granvik et al. (2012) that it was realised that there is a steady-state population of small Earth's natural satellites. Asteroids temporarily captured by the Earth can be regarded as a sub-population of the continuously replenishing NEO population. They originate either as direct captives from the NEO populations (Kwiatkowski et al. 2009, Granvik et al. 2016), or as pieces of Lunar ejecta (Gladman et al. 1995, Tancredi 1997). The direct captures are expected to be the dominant source for the population, as the ejection velocity from the Moon (2.5 km/s) acts as a threshold, restricting ejecta entering the Earth-Moon system only to those from large Lunar impacts. The a, e, i-space from which the asteroid may become captured is constrained to values close to those of the Earth (0.9 au $< a_\odot <$ 1.1 au; $e_\odot < 0.1$; $i_\odot < 2°$; cf. Paper I).

Observational evidence for Earth's temporary capture has so far been scarce. The first identified temporary capture event was the great meteor procession on February 9th 1913, observed across North America through the Canadian province of Saskatchewan to the Bermudan islands, and up to off the coast of Brazil. This event has been thoroughly described by Chant (1913). In the unusual event, the meteors processed horizontally through the atmosphere over the continent. The painting describing the procession has been reprinted in Paper II.

To the best of my knowledge, the first attempt of a thorough search for Earth's natural satellites was taken up by the discoverer of Pluto Clyde W. Tombaugh in the 1950s (Tombaugh 1956). Over the course of 2.5 years he covered 700 000 square degrees of the sky up to $V = 14$ and approximately 7 000 000 square degrees up to $V = 10 - 11$, using non-sidereal tracking velocities of up to 360°/day. He also attempted searching for satellites of the Moon during the Lunar eclipse of November 18th, 1956. Unfortunately, no satellites were found during these surveys.

At the time of its discovery in 1991, the asteroid 1991 VG gained attention due to its elliptic geocentric eccentricity (Tancredi 1997). In terms of Paper I it can be classified as a long-captured TCF (de la Fuente Marcos & de la Fuente Marcos 2018). Discovered by the Catalina Sky Survey, the asteroid 2006 RH_{120} was the first TCO to be confirmed to be a natural body during the rotation around the Earth (Kwiatkowski et al. 2009). It made four revolutions during its one-year long capture. Also, the orbit of meteor EN130114, discovered over Czech Republic on January 13th 2014, had a 95% geocentric origin (Clark et al. 2016). The meteor was confirmed to have natural origin from spectroscopic observations.

Being on elliptic geocentric orbits, NESes have the unfortunate trait of being mixed up with artificial bodies. There is no danger of mixing up NESes with the majority of satellites which are on low-Earth and geosynchronous Earth orbits, and have characteristic sky velocities and orbits. The typical discovery sizes of NESes are in the 1 m-class (Paper III), which is also the typical size of rocket stages and defunct satellites. For example, an upper stage of the Apollo 12 rocket had escaped the Earth-Moon system before reappearing for observations in 2003 (Jorgensen et al. 2003).

The most straightforward way to distinguish between the origins of geocentric objects would be measuring the radar albedo of the candidates. However, the velocity of TCOs requires a complicated bistatic radar arrangement. Currently, calculating the area-to-mass ratio of an object is the most efficient way to distinguish the origin of the observed bodies. The area-to-mass ratio is calculated through the offset from the purely gravitational model of the asteroid's orbit caused by Solar radiation pressure. However, calculating the area-to-mass ratio sometimes requires weeks and even months of astrometric coverage of the object. In the last decade there have been two candidates for geocentric objects which eventually turned out to be artificial satellites. Initially, both the object WT1190F, which impacted Earth in the Indian Ocean off the coast of Sri Lanka on November 13th 2015 (Micheli et al. 2017), as well as the object 2018 AV_2 discovered in January 2018 were brought up as potential TCO candidates. However, their area-to-mass ratios were measured to be higher than for typical natural objects, proving their artificial origin (Paper II). The astrometric coverage required to measure the area-to-mass ratio with 5σ confidence was several days in the case of WT1190F and almost a month in the case of 2018 AV_2.

The work on the construction of steady-state population model of NEOs (Bottke et al. 2002b, Granvik et al. 2016) lead to the subsequent realization that the steady-state population also includes NESes, a sub-population of NEOs. Paper I showed directly that objects captured into the NEO population from the main belt appear on orbits from where the capture onto geocentric elliptic orbits is possible.

The size-frequency distribution of NEOs has been estimated by assessing redetection rates of asteroids up to the level of $H = 25$ (Granvik et al. 2016, Harris & D'Abramo 2015), roughly corresponding to the diameter of 35 metres. The lower end of the size-frequency distribution of NEOs (up to one metre in diameter) is constrained through bolide data (Brown et al. 2002, Brown et al. 2013). Currently, there are not enough observations of asteroids in the 1-10 metre domain. Thus, the current best estimate in that domain is an extrapolation from both asteroid and bolide data. However, combining both extrapolations does not yield unambiguous estimates. Moreover, disagreements exist even between different NEO models (Granvik et al. 2016, Harris & D'Abramo 2015, Tricarico 2017).

Due to their close approaches to Earth and extended capture durations, the NESes are an optimal population for targeted observations in the 1-10 metre domain. To constrain the size-frequency distribution, we first need to discover TCOs of different sizes. An example observational campaign utilising TCO detections with the upcoming Large Synoptic Survey Telescope is outlined in Paper III. Then, a population model of TCOs independent of any extrapolations can be constructed. This model can then be used to resolve the present disagreements.

Following Granvik et al. (2012), in Paper I, the population statistics of TCOs and TCFs are assessed. The average duration of a geocentric capture of a TCO is nine months during which they make on average three revolutions. TCFs spend on average 1.5 months in a geocentric state. At any given moment, the largest captured TCO is 70 cm in diameter. A body with 3 metres in diameter, comparable in size to 2006 RH_{120} is captured once a decade.

Recent in situ investigations of asteroids (162173) Ryugu by Hayabusa2 and (101955) Bennu by OSIRIS-REx have shown that the surfaces of hecto-kilometre-sized gravitational-aggregate asteroids (commonly known as rubble piles) are covered with 1-10 metre sized objects (Fig. 2). The current understanding is that the inner structure of a rubble pile asteroid is similar to that exposed on its surface, and the entire asteroid is kept together with weak gravitational forces. The size range of TCOs indicates that they are free-floating monolithic objects, similar in composition to boulders on surfaces of km-sized asteroids.

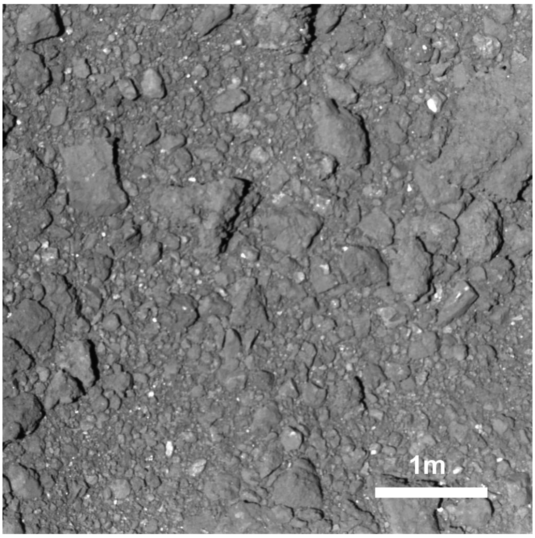

Figure 2: The surface of (162173) Ryugu photographed on October 15 at 22:40 JST using the Optical Navigation Camera – Telescopic (ONC-T) of the Hayabusa2 spacecraft. The altitude here is about 42m. Image credit: JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, University of Aizu, AIST.

Δv is a dynamical quantity which illustrates the amount of change of velocity required to reach the potential exploration target by a spacecraft (Shoemaker & Helin 1978). TCOs, previous candidates for TCOs (2018 AV_2), and TCFs occupy some of the top positions in the list of most accessible targets for spacecraft missions in terms of Δv (Benner 2010). The low Δv of TCOs, their relatively long average capture duration of nine months, and small size make them outstanding targets for sample return missions. In addition to sampling the surface of a metre-sized body, an even more ambitious goal is foreseen. Instead of picking up a small boulder from the surface of a larger asteroid, it would be possible to retrieve an entire metre-sized body, and pack it in a container with a heat shield. While the technological limit for retrieving material from interplanetary space is on the order of tens of grammes, the example of over half a century of human spaceflight has proven that re-entry of hundreds of kilogrammes from the Earth-Moon system is possible. The low Δv requirement not only helps in reaching the target, but also permits the sampling capsule to return back to Earth. In particular, candidates for meteorite analogues of C-type asteroids (carbonaceous chondrites) are underrepresented in meteorite collections (e.g. Binzel et al. 2015). Thus, should there be a situation of ample TCO mission targets, C-type asteroids may be targeted as initial mission targets.

With the realisation of the abundance of NESes, these asteroids can be seen as a test base for bold technological advancements which, upon success, could be scaled up and embedded into missions to larger and more distant objects. NESes could serve as test ground for various aspects of future asteroid missions, for example in the emerging field of asteroid resource utilisation (Granvik et al. 2013). When the abundance of NESes will be proven, various consecutive missions could be used as stepping stones for a rapid advancement of missions to more distant Solar System bodies.

The rapid brightening of NESes during their closest and fastest flyby of Earth is usually the only opportunity to detect them. This makes NESes very challenging targets for observations. With a limiting magnitude of $r = 24.7$, the observational time window lasts typically two nights (Paper III). This prevents a conventional type of a “prepared” space mission with a pre-selected target. Instead, a preliminarily launched mission into a stable orbit is a more valid option. Transfer orbits of a satellite hibernating on a halo orbit around the Earth-Moon system’s L_2 point to an observed TCO, triggered upon an observation, have been studied (Chyba et al. 2014, Brelsford et al. 2016). These studies show that such a transfer is plausible. The hibernation in waiting for a suitable target would be similar to ESAs recently selected Comet Interceptor mission.

NESes are an example of a group of asteroids for which only exiguous data may be available. In the following chapter, I will present the orbit determination process, its application to exiguous data, and what kind of advancements can be made to enhance the possibility of their detection and to facilitate follow-up observations. I will then assess the importance of survey programmes for asteroids detection, and investigate, whether TCOs are suitable targets for the most advanced upcoming survey telescopes.

3 Orbital inversion

3.1 Overview of orbit determination methods

The observations of the motion of planets lead the Polish astronomer Nicolaus Copernicus (1543) to introduce the heliocentric model of the Solar System. Consequently, the meticulous observations of Mars by the Danish astronomer Tycho Brahe paved the way to the deriving of three laws of planetary motion by the German astronomer Johannes Kepler (1609, 1619). The motion of the heavenly bodies was further incorporated in the general model of mechanics by Newton (1687).

The first small Solar System objects observed in the sky were comets. The first confirmed literal mentions of comet observations by the Chinese astronomers date to as early as 603 BC (Stephenson & Yau 1984). The observations of comets, especially of comets 1P/Halley and D/1770 L1 (Lexell) led to the understanding of periodicity of comets on the one hand, and the effect of Jupiter and the mortality of comets on the other hand.

The first application of Newtonian mechanics to solving new astronomical problems was performed by Edmond Halley for the comet now carrying his name (1P/Halley). He hypothesized that the comet that appeared in 1531, 1607 and 1682 was the same object, and predicted its return to the inner Solar System in 1758. The perturbations by Jupiter and Saturn delayed the return compared to the prediction by almost two years. This effect was computed by Alexis Clairaut, Joseph Lalande and Nicole-Reine Lepaute (Lancaster-Brown 1985). Their prediction was only one month off the true return, and was one of the first independent observation-based confirmations done for Newtonian mechanics. The initial geometric approach to Newtonian mechanics permitted solutions only for parabolic orbits. Euler (1744) derived the first analytical solution for orbit determination which was expanded to all conic sections by Lambert (1761, 1773).

The discovery of the first asteroid, now dwarf planet (1) Ceres by Guiseppe Piazzi in 1801, and the problem of its subsequent recovery after its disappearance behind the Sun paved the way to the new branch of applied mathematics developed by Gauss

(1809). In particular, Gauss' method for computing an orbit from three observations remains an often used starting point for orbital inversion. Gauss also derived the theory of least squares for overdetermined systems, which was independently derived by Legendre (1805) for comets.

In general, a set of three observational pairs of R.A. and Dec. is required for computing a well-defined orbit, as in the case of Gauss' method. Further developments in orbit determination from three observations yielded several practical methods, such as the Gauss-Encke-Merton method and the Moulton-Väisälä-Cunningham (for details, see Marsden 1985, and references therein). If only two observations are available, it is still possible to derive an orbit. However in this case, the problem is underdetermined, and requires additional constraints. In some cases, fitting a circular orbit can be attempted for two observations (Dubyago 1961). This is, however, definitely not the case with comets. The methods by Väisälä (1939) and Orlov (1939) make an assumption that the objects are near perihelion at discovery. Then either the perihelion distance or eccentricity of the orbit is guessed, respectively of the method. Especially Väisälä orbits have proved to be useful for preliminary solutions. While the discovery at perihelion used to be a generally valid assumption for the previous generation of asteroid surveys (Marsden 1991), current surveys detect asteroids also at other orbital longitudes. In particular, the geometry of the scanning law of the Gaia mission completely prevents it from observing in the brightness-wise most advantageous opposition direction (Paper IV).

The methods by Gauss and its derivatives have been a backbone of orbit determination for over two centuries, and are still applicable today in cases of abundant observations over a long period of time. For initial orbit determination with exiguous data and short time spans, the distribution of elements cannot be assumed Gaussian (Muinonen & Bowell 1993). Using optimisation methods in case of exiguous data may lead to finding a local minimum solution, which may not be the best possible one. Instead, with statistical methods, the aim is to compute a representative sample of possible solutions. The realisation of these facts subsequently paved the way for the development of Bayesian methods for initial orbit determination.

3.2 Processing astrometric systematic errors

Generally, in asteroid astrometry, the systematic errors are considered negligible compared to random errors. However, significant systematic effects do appear in positions and proper motions of frequently-used stellar catalogues such as, e.g. USNO and UCAC (Chesley et al. 2010, Farnocchia et al. 2015, Kuznetsov et al. 2016). The extent of systematic errors varies throughout the sky, being on the order of tens of milliarcseconds at highest. Especially in cases when astrometric reductions rely on a single star catalogue, the systematic errors need to be properly taken into account.

Systematic errors are also present in the short-term processing of Gaia. The high precision of Gaia long-term data is achieved through elaborate iterative calibration processes. However, for short-term processing, the only available calibration data is of substantially low quality, increasing the effect of systematic errors.

The effect of the systematic error on the observations can be lowered by calculating the so-called normal point of adjacent observations (Paper VII). Following Gaia nomenclature, derived from its mode of operation, I will call single-night combinations of observations *transits*. Each transit has N observations, and the movement of an asteroid within a transit can be assumed linear. The nominal approach of treating each point within a transit as a separate observation leads to unrealistically wide predictions of asteroid ephemerides, rendering them virtually useless for follow-up observations. In the normal-point method, each transit is collapsed to a single point. In what follows, the index i refers to a transit, where j refers to a single observation within a transit. The date for the normal point is

$$t_i = \frac{1}{N_i}\sum_{j=1}^{N_i} t_{ij}. \tag{3.1}$$

Since the linearity of the movement of an asteroid is assumed, the problem can be formulated with the following notation: first, the matrix M_i is constructed with epochs of single observations within a transit; Φ_i combines all epoch matrices M_i; and Y_i combines all the R.A.-Dec. observation pairs. The vector Q_i represents the unknown normal points and motions:

$$\begin{aligned}\begin{pmatrix}\alpha(t)\\ \delta(t)\end{pmatrix} &= \begin{pmatrix}\alpha_i + \dot{\alpha}_i(t-t_i)\\ \delta_i + \dot{\delta}_i(t-t_i)\end{pmatrix} \equiv M_i(t)Q_i,\\ M_i(t) &= \begin{pmatrix}1 & 0 & t-t_i & 0\\ 0 & 1 & 0 & t-t_i\end{pmatrix}, \quad Q_i = \begin{pmatrix}\alpha_i\\ \delta_i\\ \dot{\alpha}_i\\ \dot{\delta}_i\end{pmatrix},\end{aligned} \tag{3.2}$$

$$Y_i = \begin{pmatrix} \alpha_{i1} \\ \delta_{i1} \\ \vdots \\ \alpha_{iN_i} \\ \delta_{iN_i} \end{pmatrix}, \qquad \Phi_i = \begin{pmatrix} M_i(t_{i1}) \\ \vdots \\ M_i(t_{iN_i}) \end{pmatrix}, \tag{3.3}$$

We also define the block-diagonal inverse error covariance matrix $\Lambda_{Y_i}^{-1}$

$$\Lambda_{Y_i}^{-1} = \begin{pmatrix} \Lambda_{\epsilon,i1}^{-1} & \dots & 0^{2\times 2} \\ \vdots & \ddots & \vdots \\ 0^{2\times 2} & \dots & \Lambda_{\epsilon,iN_i}^{-1} \end{pmatrix}. \tag{3.4}$$

where $\Lambda_{\epsilon,ij}$ is the covariance matrix for the random error in the single data point j of transit i and $0^{2\times 2}$ denotes a 2×2 null matrix.

The solution for the normal point vector Q_i and its covariance matrix Λ_{Q_i} with the general linear least-squares method is

$$\begin{aligned} Q_i &= \Lambda_{Q_i} \Phi_i^{\mathrm{T}} \Lambda_{Y_i}^{-1} Y_i, \\ \Lambda_{Q_i} &= (\Phi_i^{\mathrm{T}} \Lambda_{Y_i}^{-1} \Phi_i)^{-1}, \end{aligned} \tag{3.5}$$

The resulting normal-point observations and motions are defined as

$$\begin{aligned} (\alpha_i, \delta_i) &= (Q_{i_1}, Q_{i_2}) \\ (\dot{\alpha}_i, \dot{\delta}_i) &= (Q_{i_3}, Q_{i_4}) \end{aligned} \tag{3.6}$$

In the case where the systematic error υ may in the long run be considered random between various batches of observations (as is the case in Paper VII, but also typically in observations with variable systematic errors of sky catalogues throughout the sky), its behaviour is similar to the random errors in the long run. In that case, the covariance matrix of the combined Gaussian random variable $\epsilon + \upsilon$ is

$$\Lambda_i = \Lambda_{\epsilon,i} + \Lambda_{\upsilon,i}, \tag{3.7}$$

where $\Lambda_{\epsilon,i}$ is the 2×2 upper left-hand corner block of Λ_{Q_i}. The current definition for the observation and its error covariance matrix allows formulating the orbital inversion problem in terms of random errors, recalling that the within-transit systematic error has been accounted for via Eq. 3.7. The effect of the systematic error is reduced with the batch of systematic errors from individual observations rendered into a single random error.

For subsequent Gaia data releases, systematic errors are small, and diminish due to the iterative solutions and whole sky coverage. However, the single-day data used for asteroid alerts rely only on lower-quality calibration data, yielding systematic errors on a non-negligible level. Furthermore, the observational pattern of Gaia is unique, requiring a separate approach.

3.3 Orbit determination with random-walk ranging

The problem of asteroid orbit determination constitutes solving six parameters from a differential equation. Typically, for Solar System bound elliptic orbits, the parameters solved are represented as a set of Keplerian or cometary elements, or as a Cartesian orbital state vector.

The data is usually exiguous in the cases of initial asteroid orbit determination. Instead of aiming for the most accurate orbit, for initial discovery and short observational time coverage it is more sensible to calculate a representative sample of possible orbits and predicted ephemerides for follow-up observations. Thus, the orbit determination problem becomes probabilistic instead of deterministic. Here, I will present a brief introduction to Bayesian orbital inversion with statistical ranging, and subsequent developments. An overview of various statistical ranging-based methods is given in Virtanen (2005b).

The basic observation equation describes the relation between observed and computed positions:

$$\mathit{\Psi} = \boldsymbol{\Psi}(\mathbf{P}) + \epsilon + \upsilon \tag{3.8}$$

Here $\mathit{\Psi}$ is a vector of sky positions, $\mathbf{P}$ are the six orbital elements (e.g. cometary, Keplerian, or Cartesian) at the specified epoch t_0. The function $\boldsymbol{\Psi}(\mathbf{P})$ depicts the topocentric positions with light-time correction computed with the orbital elements at the given epoch, and ϵ and υ correspond to random and systematic errors, respectively.

In the Bayesian inverse theory (e.g., Muinonen & Bowell 1993), the a posteriori p.d.f. of orbital elements is proportional to the a priori and observational error p.d.f:s

$$p_{po}(\mathbf{P}) = \frac{p_{pr} p_{\epsilon+\upsilon}(\Delta\Psi(\mathbf{P}))}{\int p_{pr} p_{\epsilon+\upsilon}(\Delta\Psi(\mathbf{P})) d\mathbf{P}} \tag{3.9}$$

where the observed-computed sky residuals

$$\Delta\Psi(\mathbf{P}) = \Psi - \mathbf{\Psi}(\mathbf{P}) \tag{3.10}$$

The a priori p.d.f. is here a constant, introducing Jacobians in orbital element transformations. For a set of Cartesian elements, the a posteriori p.d.f. is

$$p_{po}(\mathbf{P}) \quad \propto \quad e^{\frac{-\chi^2(\mathbf{P})}{2}}, \tag{3.11}$$

$$\chi^2(\mathbf{P}) \quad = \quad \Delta\Psi^T(\mathbf{P})\Lambda^{-1}_{\epsilon+\upsilon}\Delta\Psi(\mathbf{P}) \tag{3.12}$$

It should be noted that, in the case of a non-informative constant a priori p.d.f., the a posteriori p.d.f. is dependent on the initial selection of the coordinate vector **P**. The a priori p.d.f. may also be informative. The informative a priori p.d.f. can assign different weights to different types of orbits based on population models of asteroids (e.g., Granvik et al. 2018). The informative a priori p.d.f. can also enable combining different types of observations, for example using constraints obtained from radar observations for optical follow-up.

When using statistical ranging for orbit computation, at least two observations are required. In an overdetermined set of observations, usually the first and the last position are selected to maximize the observational coverage. The six parameters are two positions (α_1, α_2, δ_1, δ_2), which are randomly deviated within a Gaussian distribution surrounding the observational coordinates, and topocentric distances ρ_1 and ρ_2, which are drawn from a uniform distribution. The ranges are strongly correlated. A trial orbit, uniquely corresponding to a set of six parameters, is calculated, and is accepted if it fits all the observations based on the pre-defined χ^2 threshold. A typical threshold is the requirement of the sky-plane residuals to be within the 3σ limit (where σ is the standard deviation), corresponding to the 99.7% confidence value. Each orbit is also assigned a weight relative to the goodness of fit of the constantly updated best-fit orbit. This method, called statistical ranging (Virtanen et al. 2001, Muinonen et al. 2001), is a backbone for further advancements in development of various ranging methods. Statistical ranging may also use input orbits to constrain the acceptable ranges in cases when more observations eventually become available.

While statistical ranging is performed with only two observations, the acceptance criteria takes into consideration all available observations. Statistical ranging is robust as it is designed to randomly sample the entire six-parameter orbital phase space for optimal solutions without any assumptions, but it also makes the method computationally intense.

Markov-chain Monte Carlo ranging (Oszkiewicz et al. 2009) is a further development of statistical ranging. Here, instead of rigorously sampling throughout the entire (α, δ, ρ)-phase space, the acceptance of the proposed orbital elements depends on the probability density value of the previous accepted orbit by computing the ratio a_r (Metropolis-Hastings algorithm):

$$a_r = \frac{p_{po}(\mathbf{P'}) J_j}{p_{po}(\mathbf{P_j}) J'} \tag{3.13}$$

Here J' and J_j are determinants of Jacobians from spherical topocentric coordinates to parameters of the candidate orbit and the previous accepted orbit, respectively. The orbit is always accepted as a solution if the quotient $a_r \geqslant 1$. If $a_r < 1$, then the proposal orbit is a worse fit than the previous one, but it may get accepted with the probability a_r when sampling a random number from a uniform distribution between 0 and 1. The advantage of MCMC ranging is its computational speed. However, it is not as rigorous as the statistical ranging algorithm, because some of the phase space regions may be left unexplored if the solutions are confined to a local minimum.

Random-walk ranging (Paper V) is a method aimed at combining the rigorousness of statistical ranging, and the computational speed of MCMC ranging. Instead of sampling in a MCMC manner, it is advantageous to sample the entire phase space below a pre-defined $\chi^2(\mathbf{P})$ level. The value

$$\Delta\chi^2(\mathbf{P}) = \chi^2(\mathbf{P}) - \chi^2(\mathbf{P}_0) \tag{3.14}$$

is sampled in the orbital phase space, where an arbitrary acceptable p.d.f. $\mathbf{P}_0$ is assigned a non-zero value. MCMC sampling optimised for reaching the acceptable region is initially used. In the acceptable region, the a posteriori p.d.f. values are assigned as the weights for the sample orbital elements. The final weight factor w_j is obtained through division by a determinant of a proper Jacobian value:

$$w_j = \frac{p_{po}(\mathbf{P}_j)}{J_j} \tag{3.15}$$

As for MCMC ranging, in random-walk ranging the solutions may include repeating sets of orbital elements. Random-walk ranging has been implemented and is in continuous use for the short-term processing of newly discovered asteroids by Gaia (Paper VI).

4 Survey programmes and asteroids

4.1 Stellar surveys

Stellar surveys act as a base for asteroid surveys, through establishing the coordinate system and providing reference stellar positions for astrometric reductions. A thorough introduction on the development of stellar cataloguing and surveys, sometimes called by the broad term *uranography* or *astrography* is given in chapter 24 of Karttunen (2009), and a compilation of advancements of astrometric accuracy and number of observations through the ages by Høg (2018). The improvement of the precision of astrometric positions is presented in Fig. 3.

A fresh generation of surveys often represents a step in technology, and results in the comprehension of a new astronomical phenomenon or discovery of a new population of objects. The observing facilities could be divided into two subcategories: general-purpose observatories, dedicated to all sorts of astronomical observations, one phenomenon at a time; and survey telescopes, dedicated to building a statistically significant picture of a specific astronomical subfield. Traditionally, an astronomical object is discovered in a dedicated survey. Should the object require further attention, the object is assigned follow-up observations by general-purpose telescopes. The sizes of telescopes dedicated to astronomical surveys have typically lagged behind the construction of largest telescopes of their time. When a larger telescope get commissioned, the smaller ones gradually become underbooked or even decommissioned, and in some cases become refurbished exclusively for survey purposes. This is especially the case with wide-field telescopes, with, e.g., Schmidt optics. In the recent decades, the consolidation of efforts, and improvements in automatic data processing have led to the emergence of synoptic survey telescopes, where several subfields of astronomy participate and benefit from the project. Prime examples of such telescopes are the ongoing Gaia mission and the Large Synoptic Survey Telescope, expected to commence its operations in early 2020s.

The task of cataloguing heavenly bodies has been performed up from the early ages of humankind. The earliest known stellar catalogues are found among Baby-

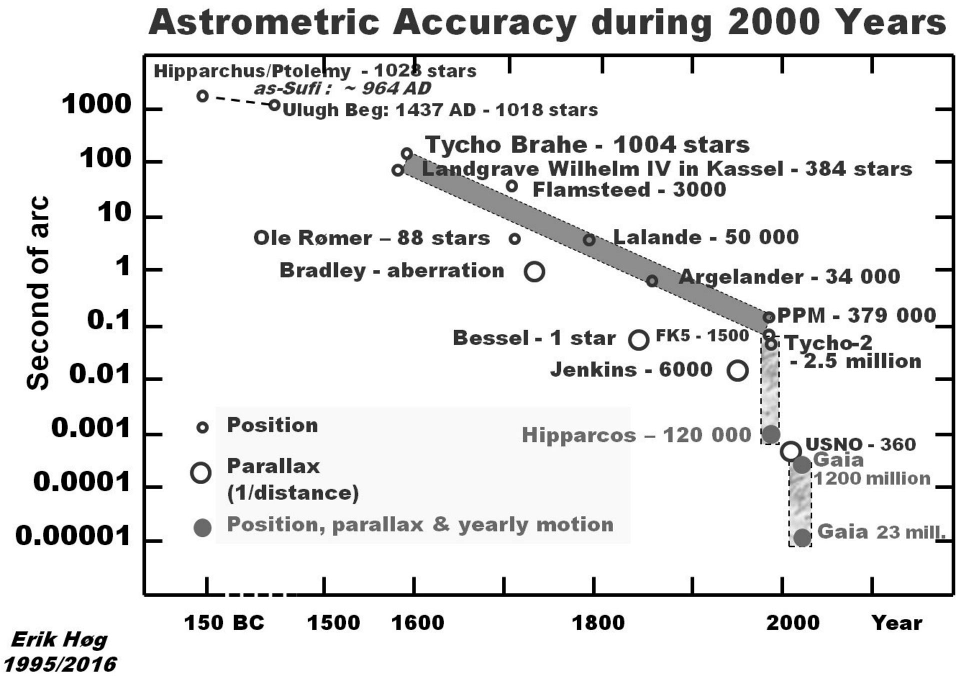

Figure 3: The development of accuracy of astrometric surveys and number of observed stars through the ages. Reprinted with permission from Prof. Erik Høg.

lonian clay tables from Mesopotamia, and date to the second millenium BC. The sexagesimal division into minutes and seconds as well as the division of a circle into 360° have been inherited from Sumerian and Mesopotamian astronomers and mathematicians. Unrelatedly, a stellar catalogue depicting planets and brightest constellations has been found in Egypt on the ceiling of the tomb of Senenmut (Theban tomb No. 353), a government official in the time of the pharaoh Hatshepsut (ca. 1473 BC). The ancient Egyptians have also had the knowledge of the variability of the eclipsing binary Algol (Jetsu et al. 2013).

From antiquity, perhaps the most widely known is the stellar catalogue of Hipparchus of Nicaea. It comprises 1022 stars visible with the naked eye. Comparing his catalogue to a previous one of Timocharis of Alexandria, and noticing the shift in longitudes of the stars, Hipparchus discovered the apparent precession of equinoxes. This catalogue has been passed onwards through the works of Claudius Ptolemy in his treatise best known as Almagest (see Toomer 1984, for a contemporary English translation). Almagest is also the first source to introduce the magnitude system of stellar brightness based on the logarithmic properties of the human eye. The magnitude system is also usually attributed to Hipparchus, and has survived to this day with minimal modifications.

The Almagest catalogue has been the prime stellar catalogue in use for over a millenium. Extensive independent measurements of stars visible with the naked eye have also been performed by the Persian astronomer Abd al-Rahman al-Sufi in the X century (with first literary mention of Andromeda galaxy as a cloud, and the Large Magellanic Cloud), and by the sultan of Samarkand Ulugh Beg in the XV century.

In the wake of the Copernican revolution, the Danish astronomer Tycho Brahe realized that the planetary tables based on Copernicus' theory were not precise. Consequently, Tycho Brahe constructed a new catalogue, with several orders of magnitudes more precise observations of stellar positions than its predecessors — still several decades before the invention of the telescopes. As mentioned in Chapter 3, Tycho Brahe's observations of planets, especially of Mars, lead to the discovery of Kepler's laws. Moreover, in 1572 he, among other observers, noticed a new bright star in the constellation of Cassiopeia. This observation, now known to have been a supernova, was a major drive to shift from the Aristotelean paradigm of the eternal and unchangeable realm of stars.

Based on the observations of Tycho Brahe, and complemented with the southern sky stellar observations by the Dutch navigator Pieter Keyser, Johann Bayer published a stellar catalogue named *Uranometria* in 1603. Bayer introduced the naming scheme of stars, which is still used for the brightest objects in each constellation.

The British astronomer John Flamsteed tripled the number of stars known in Tycho Brahe's catalogues in the first telescopic survey, published posthumously as *Historia coelestis Britannica* in 1725. This survey was, however, limited only to the stars visible from the Greenwich observatory. The first stellar whole-sky catalogue based on telescopic observations was *Histoire Céleste Française* by Jérôme Lalande in 1801. Both Flamsteed and Lalande created their respective cataloguing schemes, which are still used alongside with other systems.

The next major advancement was the work by Friedrich Argelander, and his *Bonner Durchmusterung*. It was the most extensive survey made before the invention of photography. Since the southernmost stars are not observable from Bonn, it was later complemented with observations from Córdoba (Argentina) and Cape Photographic (Cape Town, South Africa) *Durchmusterungs*. The catalogue extended to $V \approx 9 - 10$, with a typical accuracy of $0.1''$. The combined number of observed stars in all *Durchmusterungs* was close to a million. With the large amount of stellar positions, the investigation of the structure of the Milky Way galaxy could begin, followed by the realisation of existence of other galaxies.

By going towards fainter objects, the workload becomes unbearable for a single observatory. Performing large stellar surveys lead to establishing an international collaboration, *Astronomische Gesellschaft*, distributing responsibilities for astrometric observations to facilities around the world.

The invention and adaption of photography lead to an international sky cataloguing project called *Carte du Ciel* in the end of the XIX century, with the goal to catalogue the entire sky down to the absolute magnitude 11. It included 16 observatories around the world. While it took several years to perform the observations, the reduction of data took decades. The final release of *Carte du Ciel* was published in 1959. The *Carte du Ciel* data has recently resurfaced for the purpose of measurements of proper motion of the stars combined with modern spaceborne astrometry data (Lehtinen et al. 2018). In the decades following *Carte du Ciel*, there has not been an attempt of a global full-sky cataloguing survey, as the emerging field of astrophysics took over telescopes.

All previously mentioned surveys were performed with position and proper motion measurements. The addition of parallax measurements is essential in providing the distance of the observed star. Together with position and proper motion measurements, parallax measurements allow the construction of a three-dimensional map of the surroundings of the Sun. The required astrometric accuracy for parallax measurements of stars in the Solar environment is of sub-milliarcsecond level. The significant step in accuracy of astrometric observations was achieved with spaceborne astrometry, and the Hipparcos mission.

ESAs Hipparcos mission (for a concluding overview, see Perryman 2009) operated from 1989 to 1993, and despite its partial launch failure, was the first successful spaceborne astrometric mission. In the resulting Hipparcos catalogue, containing over 130 000 stars up to magnitude 9, the astrometric position of stars was improved by two orders of magnitude compared to ground-based surveys. A less accurate Tycho-2 catalogue was also produced, with 2.5 million stars and completion to magnitude 11. The astrometric accuracy of Tycho-2 positions is on par with the most accurate ground-based catalogues, but with significantly smaller systematic errors. Hipparcos was a purely stellar cataloguing mission. Only a handful of asteroid observations was processed from the Hipparcos data, separately and afterwards (Hestroffer et al. 1995). The Gaia mission was built on the legacy of Hipparcos.

The success of the Hipparcos mission helped reviving the interest in the field of astrometry. A significant effort of digitising photographical plates of over 50 years of various surveys resulted in the widely used USNO catalogues (e.g., Monet et al. 2003). A number of modern CCD-based stellar cataloguing ground-based efforts emerged. A successor to USNO catalogues, the UCAC catalogue, was an extensive ground-based survey using CCDs and automatic star measurements. The final release of the UCAC catalogue, in 2004, included on the order of 100 million stars down to limiting magnitude 16.

In particular, various USNO catalogues have been widely used for astrometric reduction of asteroid observations due to their faint limiting magnitude of 20. These catalogues however do not always take proper motions of stars into account. In addition, systematic errors in varying parts of the sky have been identified for these surveys (Chesley et al. 2010, Farnocchia et al. 2015). Thus, the presence of systematic errors in stellar catalogues is a significant factor reducing the accuracy of asteroid astrometric observations. Inverting, asteroid observations help revealing the systematic errors in stellar catalogues. The method of reducing the effect of systematic errors has been presented in Paper VII.

4.2 Dedicated asteroid observations

Guizeppe Piazzi discovered (1) Ceres in 1801. Prompt discoveries of (2) Pallas and (4) Vesta by Heinrich Olbers and (3) Juno by Karl Harding followed in the next decade (an overview of earliest asteroid discoveries is given by, e.g., Foderá Serio et al. 2002). After initial excitement of discovering new "planets" in the Solar System, it was soon realised that the discovered objects were much smaller than other known planets. This hindered the enthusiasm of observers, and the time span between the discoveries of (4) Vesta and (5) Astraea was an astonishing 38 years (1807-1845).

Before the 1950s, discovery of asteroids rested on shoulders of individual observers. Prominent observers of the XIX and first half of XX century include Christian Heinrich Friedrich Peters, Johann Palisa, Max Wolf, Auguste Charlois, Grigory Neujmin, Yrjö Väisälä, and Karl Wilhelm Reinmuth. For the first 90 years the observations were performed with naked eye; Max Wolf was the first one to use astrophotography for discovering new asteroids starting in 1891.

Like for many subfields of astronomy, the statistical approach has played a very prominent role in asteroid studies since the very beginning. Notable discoveries of the early ages in the studies of asteroids were the resonant Kirkwood gaps in the main asteroid belt (Kirkwood 1869) from the 97 asteroids known at the time as well as identifying first three collisional Hirayama families (i.e., Eos, Koronis, and Themis) in the main asteroid belt from 790 known asteroids (Hirayama 1918). These are remarkable examples of advances made by examining the statistics of asteroid orbital elements before the era of dedicated asteroid surveys.

The first dedicated asteroid survey was the Yerkes-McDonald survey (Kuiper et al. 1958) with a limiting magnitude of 16.5. It enabled the first investigation of the size-distribution of asteroids. The Palomar-Leiden survey (van Houten et al. 1970) and its three subsequent follow-up campaigns of Jupiter Trojans were not as extensive in sky coverage as the Yerkes-McDonald survey, but it went down to a limiting magnitude of 20. The Palomar-Leiden survey unveiled information about phase angle dependencies of asteroids. Additionally, the results from the survey were used to construct the first size-frequency distribution law of MBAs. The astronomers behind the Palomar-Leiden survey, Tom Gehrels, Ingrid van Houten-Groeneveld and Cornelis van Houten are up to this day the three individual astronomers with most asteroid discoveries attributed by the Minor Planet Center. The Palomar-Leiden survey was well ahead of its time, and the discovery rates were not surpassed until only a decade later, with the first targeted photographic survey for NEOs performed by Helin & Shoemaker (1979). It resulted in many accompanying discoveries of MBAs, and a first estimate of the NEO population.

However, the NEO surveys did not emerge until after the realisation of impact hazard of asteroids. The understanding came with the discovery of the ubiquitous iridium layer originating from the asteroid impact on the border of the Cretaceous and Tertiary geologic periods (Alvarez et al. 1980). This layer coincided with the time of mass extinction of 75% plant and animal species (including dinosaurs). This paved the way for NEO surveys mapping the threat. A comprehensive overview on NEO search programmes is given by Jedicke et al. (2015), and the development of the number of discoveries of NEOs over the last decades is presented in Fig. 4.

The recognition of the potential asteroid threat coincided in time with the adaptation of CCD technology as astronomic detectors. The 10 000th overall asteroid was discovered in 1989, but with automated surveys, the number has increased dramatically in 30 years — the number of discovered asteroids exceeds 700 000 as of 2019. Although NEOs are primary discovery targets, the majority of discovered asteroids are still in the main belt.

The first CCD-equipped survey programme was Spacewatch, which was also the first survey to automatically discover an asteroid in 1990 (Rabinowitz 1991, Scotti et al. 1992). Currently, Spacewatch has shifted from discovery to performing follow-up observations of asteroids discovered by other surveys (McMillan & The Spacewatch Team 2007). Other major surveys that have substantially contributed to the discovery of asteroids in the era of CCDs and automated image processing, but have ceded operations, are the Near-Earth Tracking programme (NEAT, Pravdo et al. 1999); the Lowell Near-Earth Object Survey (LONEOS, Bowell et al. 1995); and Lincoln Near-Earth Asteroid Research (LINEAR, Stokes et al. 2000). Some of

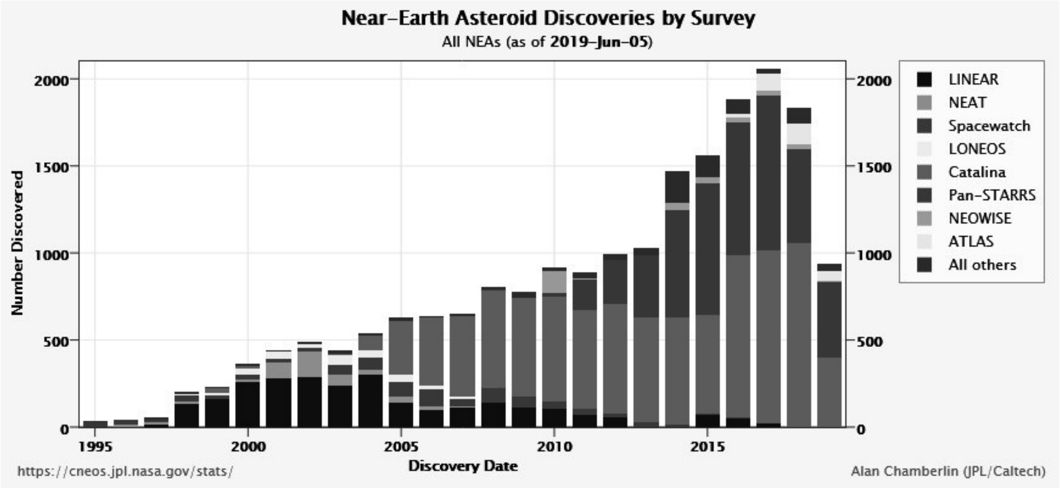

Figure 4: The number of discovered NEOs by survey as of June 5th 2019. The two primary contributors in the last years have been the Catalina Sky Survey (lighter) and Pan-STARRS (darker). Image courtesy: NASA/JPL-Caltech.

these programmes have benefited from synergy with military satellite detection activities. Since 2005, the main dedicated contributor to asteroid discoveries has been the Catalina Sky Survey (CSS), which has enabled the discoveries of ten-metre-class NEOs. From among these, the first three asteroids (2008 TC_3, 2014 AA and 2018 LA) which have been detected prior to impacting Earth have been discovered by Richard Kowalski from the CSS.

4.3 Undedicated and synoptic surveys

In this section I make the distinction between *undedicated* and *synoptic* surveys in the context of asteroid observations. An undedicated survey is a programme with a primary goal in some other subfield of astronomy, (e.g. surveying galaxies), but which nevertheless contributes to asteroid observations. A synoptic survey is a programme which incorporates technical decisions in its design and scheduling to accommodate the requirements of several different subfields of astronomy.

Sky surveying, detecting transient phenomena and moving objects, can benefit from cooperation in the era of automatic data reduction. This has lead to the construction of several synoptic surveys. The word “synoptic” refers to giving a broad view on different aspects of astronomy at the same time. Out of a list of important astronomical synoptic surveys, a particular focus is given to two outstanding programmes: Gaia and the Large Synoptic Survey Telescope (LSST) which will be discussed in sections 4.4 and 4.5, respectively. It should be noted that LSST will be the Goliath of ground-based surveys, and will benefit from experience of previous survey systems to ensure the completeness of its ambitious goals.

Within general-purpose astrometric surveys all kinds of astronomical objects are processed. The apparent motion of Solar System objects makes them easily distinguishable from all other sources. However, asteroids require separate procedures for processing the moving object data. All surveys designed with a certain purpose have specific observational biases. For example, asteroid surveys are usually dedicated towards discovering NEOs, with a tendency to observe in the ecliptic plane, and especially in the direction of the opposition. Cosmological surveys, on the contrary, tend to avoid the ecliptic plane due to extinction by zodiacal dust, while general purpose all-sky surveys have an otherwise biased view on the entire asteroid population compared to NEO surveys.

Cataloguing every concluded, ongoing and future survey with any significant contribution to the investigation of asteroids is well beyond the scope of this thesis. Here, a sample of prominent surveys is introduced, with a purpose of illustrating the kinds of advancements the field of asteroid research can achieve with the help of undedicated and synoptic surveys. While the main scientific goal of an astronomical survey would not be related to asteroid science, in the course of collecting data asteroids are observed anyway. Survey programmes frequently include dedicated Solar System science teams and specific data reduction processes.

Pan-STARRS 1, a prototype telescope for an array of four similar 1.8-metre telescopes, with a purpose of detecting various transient events, was the first facility particularly designed with synoptic properties (Kaiser et al. 2002). Pan-STARRS is on par with CSS on asteroid discoveries since the mid-2010s, but is expected to surpass CSS in number of discoveries, as it can observe asteroids down to magnitude $r = 23.2$. The Pan-STARRS survey introduced the Moving Object Processing System (MOPS, Denneau et al. 2013), a versatile system for asteroid detections, which uses efficient techniques to link detections of moving objects. A second telescope in the array, Pan-STARRS 2, is operational since 2018. Also, since then, Pan-STARRS 1 dedicates 90% of its observation time to NEO discoveries.

Another prominent ongoing synoptic survey is the Zwicky Transient Facility (ZTF, Bellm et al. 2019). Designed primarily for the detection of transient objects such as supernovae, ZTF is used as the test ground for various LSST automatic processing systems such as real-time processing of transient and moving objects, and the alert stream. In terms of asteroid science, ZTF is, e.g., used to detect and monitor the outbursts of known and new active asteroids. ZTF has an exceptionally large field of view of 47.7 square degrees, and is able to reach magnitude 20.5.

While being synoptic, surveys still often have a primary goal, with the performance optimized towards a specific task. An example of such a facility aimed towards the NEOs is the Asteroid Terrestrial-impact Last Alert System (ATLAS, Tonry et al. 2018). Its primary goal is to detect asteroids which are on the way to impact Earth, but it also produces alerts for supernovae and other transient events, such as gamma-ray burst optical afterglows, and the optical counterpart to a neutron-star merger releasing gravitational waves. The specialty of ATLAS is its ability to survey the entire sky in just two nights.

General purpose surveys have in particular reinforced the physical characterisation of asteroids. They are usually equipped with photometric filters. The most abundant asteroids, MBAs, appear as point sources, as typical integration times of general purpose surveys are on the order of minutes. The basic photometric reduction can then be performed with general-purpose tools.

Initially, although the brightness of asteroids was recorded, dedicated NEO surveys did not include colour information. After the realisation that the reflectance spectra of asteroids are illustrative of their compositions (McCord et al. 1970) the statistical approach infiltrated also the studies of the composition of asteroids. The photometric (Tholen 1989) and spectroscopic (Bus et al. 2002, DeMeo et al. 2009) asteroid taxonomies were derived by limited targeted asteroid surveys, and the current taxonomies were initialised from a sample of some hundreds of asteroid colours and spectra. However, the main corpus of photometric data comes from the general-purpose surveys.

A prominent example of a photometric survey where asteroids are not primary targets, but the outcome to the asteroid science is benificial is the Sloan Digital Sky Survey (SDSS, York et al. 2000), which was primarily designed to map galaxies in one third of the sky in five photometric optical bands. It also included the Moving Object Catalogue (Ivezić et al. 2002) which at the end contained photometric information for about 100 000 asteroids. Out of these, a selection of over 10 000 best-quality objects was made to interpolate their photometry to low-resolution spectrometry. Combining these colours-turned-spectra with their respective orbital distribution in the main belt, a distribution of different types of asteroids as a function of their semimajor axis was constructed (DeMeo & Carry 2013). It revealed the heterogenic distribution of asteroids of different taxonomies throughout the main asteroid belt.

An important addition to the optical ground-based surveys is the spaceborne near-infrared NEOWISE survey (Mainzer et al. 2014). Initially, the WISE mission was a whole sky synoptic infrared survey in four channels. After the coolant, required for the operation of two mid-infrared channels, was depleted, the satellite was put into hibernation. It was subsequently rewoken to use two near-infrared channels for exclusively characterising Solar System objects. Infrared data coupled with albedo measurements enables resolving diameters of asteroids. As a consequence, WISE and NEOWISE data have been the primary contributor in deriving asteroids sizes. The tasks for upcoming infrared spaceborne surveys such as the dark-energy and dark-matter survey mission Euclid (Carry 2018) and the near-infrared galaxy surveyor SPHEREx (Lisse 2018) will include characterisation of asteroids.

On a general term, the trends that improve with the evolution of surveys include: enlarging the field-of-view (ZTF, LSST); the fast survey time (ATLAS, partially LSST), precision of observations (Gaia), pushing forward the limiting magnitude (Pan-STARRS, followed by LSST). Each prominent survey has introduced a statistical approach to a new domain of asteroid studies. With new wide-field observational surveys one can expect new insights to the composition of asteroids, such as monitoring long-term activity of asteroids, sparse lightcurves for shape determination, and direct measurements of Yarkovsky and YORP effects for indirect compositional detection (e.g. rotational fission).

4.4 Gaia

Launched in 2013, Gaia is the European Space Agency's (ESA) spaceborne astrometric mission, which is as of 2019 in operation. Located in the Sun-Earth system's L_2 point, Gaia is in a constant scanning mode. The primary goal is to measure the three-dimensional positions and velocities of a billion stars as well as their astrophysical properties, corresponding to $\approx 1\%$ of all the stars in the Milky Way galaxy. Gaia is revolutionising the field of research of the structure of the Milky Way.

Gaia was built on the legacy of the Hipparcos mission. One of the major enhancements of Gaia compared to Hipparcos is the addition of other fields of astronomy to complement the stellar position and parallax measurements. The additions include: star formation history of the galaxy; stellar physics and evolution; stellar variability and distance scale; binaries and multiple star systems; exoplanets; asteroids of the Solar System; unresolved galaxies, quasars and the reference frame; relativistic effects for fundamental physics. In summary, Paper IV shows the extent of scientific goals as well as technical and operations details of Gaia, the first spaceborne synoptic astrometric mission in the visible optical range.

The particular strength of Gaia is its inner consistency, and a lack of need to rely on other observations in the long run. The initial Gaia catalogue used input from Hipparcos' Tycho catalogue, but subsequent Gaia Data releases of positions will rely on Gaia data only. Together with precise measurements of proper motions of the stars, by the end of the mission the positional errors of stars will be effectively lowered to ten-microarcsecond level, and for moving objects to a level of hundreds of microarcseconds. Gaia intermediate Data Releases have already replaced other stellar catalogues as references for astrometric reductions of moving objects – Data Release 2 in 2018 has achieved sub-milliarcsecond accuracy (Lindegren et al. 2018). The limiting magnitude of Gaia observations is 20.7, so it is on par with e.g. the USNO-B1.0 catalogue on the number of objects, but the astrometric accuracy for Gaia is currently at least two orders of magnitude higher magnitudes higher.

The treatment of Solar System objects by Gaia is two-fold. The main contribution of Gaia to asteroid science comes through the long-term processing pipeline. Complementing the iteratively-processed observations of known objects, Gaia also produces short-term alerts for newly discovered bodies.

Together with astrometric positions, intermediate data releases will include an increasing amount of asteroid orbit solutions calibrated with exclusively Gaia data. Gaia will also measure photometry for all observed asteroids, and optical spectra for a selection of the more bright asteroids. Due to the scanning law of Gaia, asteroids are observed at large phase angles. The disc-integrated phase curve of an asteroid can be described by the empirical H, G_1, G_2 phase function (Bowell et al. 1989, Muinonen et al. 2010, Penttilä et al. 2016). The coverage of large phase angles with Gaia will enable computing the phase function and provide photometric classes for thousands of asteroids through assessing the steepness of their phase curves (Muinonen et al. 2019).

The distribution of Gaia data happens through iterative data releases, improving positions with each iteration. A first sample of asteroid long term data was released in the Data Release 2 in 2018, and is presented in Gaia Collaboration et al. (2018). For Solar System objects, the orbit determination accuracy for main-belt asteroids will improve by a factor between 5 and 20 compared to current ground-based data. The uncertainty in the factor is due to the duration of the mission. The accuracy of Gaia observations paves the way to detecting even subtle effects, for example small changes in semimajor-axis due to the Yarkovsky effect for a high number of objects. The long-term processing of Gaia will also include low-resolution spectroscopy of asteroids (Delbò et al. 2012), rotational properties (Cellino et al. 2006), rotation periods, spin axis directions, and convex shapes (Ďurech & Hanuš 2018), and mass determination for a number of objects (Siltala & Granvik 2017). The precise astrometry of Gaia is an invaluable asset for predicting stellar occultations (Tanga & Delbò 2007).

In addition to providing high precision positions of known asteroids, Gaia is also discovering new asteroids. Most asteroid surveys target the ecliptic plane. Being a whole-sky survey, Gaia has the advantage of discovering in particular main-belt asteroids with high inclinations, and asteroids with orbits lying entirely within Earth's orbit (known as inner-Earth asteroids, or Atiras). The purpose of the short-term processing of Gaia asteroid data is to provide new discovery alerts for ground-based follow-up observers. The daily processing of Gaia asteroid data is presented in Paper VI. The daily processing chain starts with the identification of known orbits, and continues through centroid fitting, transit constructing, linking, orbit determination to the distribution of alerts to ground-based follow-up observers. The new orbital inversion method implemented in the processing chain is presented in Paper V, and the method to deal with systematic errors in the daily processing chain is presented in Paper VII.

4.5 Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST, Ivezić et al. 2019) is an upcoming synoptic facility, as of 2019 under construction on Cerro Pachón in northern Chile. Full scientific operations are expected to commence in 2022. LSST will cover the entire southern sky every four nights. LSST is the first facility to combine a multi-metre telescope with extremely wide-field optics and a dedicated survey mode. The four main science themes of LSST are:

- Probing Dark Energy and Dark Matter
- Taking an Inventory of the Solar System
- Exploring the Transient Optical Sky
- Mapping the Milky Way

Major advancements are expected within each science theme. Examples of programmes relevant for each science theme include: obtaining a significant sample of type 1a supernovae for assessing the behaviour of dark matter in the local universe; studying physical properties of sub-kilometre main belt asteroids in their capacity as potential future NEOs; detecting rogue planets through weak lensing; and extending the reach of parallax measurements to the width of the thin disk of the Milky Way by accumulating a swarm of repeated position measurements to increase astrometric accuracy.

As the name suggests, LSST is synoptic by its implicit design properties. Previous surveys, even those which have taken into account various astronomic subfields already in the design phase, do still have the primary scientific goal to which other scientific programmes need to adapt. What makes LSST exceptional is a combination of the wide field of view, survey depth, and relatively short exposure times. LSST aims for a compromise between its four main science goals in its observational cadence design. The debate on the final observational cadence is ongoing as of 2019. A top running candidate of beginning of 2019, *kraken_2026*, dedicates 90% of its time to the wide-deep-fast survey mode of the southern sky, between declinations 0° and -60°. In terms of Solar System science, the most important addition survey mode is the north ecliptic spur, a crescent-shaped portion of the sky which reaches the entire span of the ecliptic plane, with the declination offset coverage of 10°. Other additional survey modes of LSST include the long-exposure deep-drilling fields for pre-defined high priority targets, the southern sky spherical cap, and mapping of the Galactic plane.

Inventory of the Solar System is one of the primary science themes of LSST. LSST is expected to discover on the order of 100 000 near-Earth objects, 5 500 000 main-belt asteroids, 280 000 Jupiter Trojans, 40 000 transneptunian objects, 10 000 comets and tens of interstellar objects (Schwamb et al. 2018). Keeping in mind that the current number of all known asteroids is around 700 000, LSST alone will increase the number of known asteroids by a factor of several. The limiting magnitude of LSST, e.g. $r = 24.7$ corresponds to the ability to discover MBAs down to sizes of 100 m and TNOs down to 100 km (Jones et al. 2009). The extended deep-drilling fields also permit discoveries of TNOs as small as 10 km in diameter. Also, based on the current population estimates of NEOs (Granvik et al. 2018), over 70% of NEOs and over 80% of potentially hazardous asteroids larger than 140 m could be discovered by LSST by 2032 (Jones et al. 2018). The observations will be performed with optical $ugrizy$-filters. In the r-filter, the saturation limit is the 16th magnitude, and the 5σ threshold magnitude is 24.5. The long consistent coverage of asteroids will be also beneficial for deriving their rotational period and determining their convex shapes, although the available photometric data will be sparse in coverage.

Similarly to Gaia, LSST will systematically cover off-ecliptic fields, albeit in the southern sky only. Besides providing extensive astrometric and photometric databases (both in terms of photometry colours and lightcurves), LSST will among other things contribute to the overall understanding of the formation of the Solar System by improving the understanding of the relationship between cometary classes and their source populations, as long-period comets can be detected from further away.

As with the long chain of its predecessors, LSST is expected to reach new frontiers in astronomy by discovering and characterising new populations of astronomical objects. One particular population expected to be characterised are Earth's temporarily-captured satellites. LSST has been identified as the most suitable facility for discovering TCOs (Bolin et al. 2014). It has been showed to be the only facility among existing and upcoming ones to detect TCOs on a regular basis. In Paper III the detectability of TCOs with LSST has been assessed. The prediction based on the best estimates of the performance of LSST is that a TCO can be detected with LSST once a year with the baseline treatment. However, if a pipeline alternative to MOPS and dedicated to TCOs is constructed, then the discovery rate could improve up to the order of one discovery every two months. Additionally, Paper II shows that the size of TCOs is more indicative of their detectability than their capture duration. LSST alerts will be publicly available in nearly real time. The rapid distribution of LSST data, with subsequent processing through the dedicated pipeline, are requirements for the construction a comprehensive follow-up network for TCOs and small PHAs.

5 Summary of the publications

The thesis consists of seven journal publications, which are summarized below. The author's contribution to the papers is described at the end of each relevant section.

Paper I

Fedorets, G., Granvik, M. & Jedicke, R. (2017). Orbit and size distributions for asteroids temporarily captured by the Earth-Moon system. *Icarus* **285** 83 – 94.

Paper I continues the work by Granvik et al. (2012) to investigate the capture properties of Earth's temporary natural satellites. The paper investigates the capture efficiency, residence times in a geocentric and heliocentric frame, and the steady-state size-frequency distribution of Earth's temporary natural satellites. The analysis is extended to TCFs, to find that some of them may also become captured for months. Likewise, the analysis is extended to cover the hypothesis that, at very small values of $e_\odot$ and $i_\odot$, the population of NEOs diminishes exponentially. The paper explained the excess of the residence of captured objects in the quadrature directions. Also, the analysis in the article yielded 75 cm as the diameter of the largest TCO captured by the Earth at any given time.

The author performed all the calculations, and analysis, drew all the plots, and wrote the paper. He also revised and modified the analysis software written by Mikael Granvik to include analysis for TCFs.

Paper II

Jedicke, R., Bolin, B. T., Bottke, W. F., Chyba, M., **Fedorets, G.**, Granvik, M., Jones, L. & Urrutxua, H. (2018). Earth's Minimoons: Opportunities for Science and Technology. *Frontiers in Astronomy and Space Sciences* **5** A13.

Paper II is a review article assessing the science and technology opportunities for TCOs and TCFs, which are colloquially called minimoons. The article begins with an overview of discoveries of TCOs, with a focus on an undeservingly rarely remembered Great Meteor Precession of 1913. The paper then continues with a discussion about TCO dynamics, taking into account an astronomical and a mathematical approach to the problem of definition of capture and the equivalent of a rotation in a chaotic orbit. The origin of TCOs and TCFs from the main belt and Lunar ejecta are explained, while making a distinction between TCOs and TCFs on the one hand, and quasi-satellites on the other hand. Next, the paper addresses the issue of a lack of discovery of TCOs and TCFs, the problem of confusion with distant artificial satellites, and the means to distinguish natural objects from artificial ones through calculating their area-to-mass ratio. The article continues with the scientific implications of studying TCOs and TCFs, and is concluded with describing the possibilities for robotic missions to a TCO. A hypothetical mission could be a demonstration mission for in situ resource utilization, or retrieving an entire monolithic body to Earth for laboratory analysis.

The author provided Figures 4 and 7, and details regarding the population and observation models for LSST to the article, as well as commented overall on the manuscript.

Paper III

Fedorets, G., Granvik, M., Jones, R. L., Jurić, M. & Jedicke, R. (2019). Discovering Earth's transient moons with the Large Synoptic Survey Telescope. *Submitted to Icarus.*

Paper III investigated the detectability of TCOs with LSST. The largest challenge for TCOs is the lack of observations, and LSST has been identified as the primary facility for TCO detection. Following the results in Paper I, the paper presented a synthetic population of TCOs which was fed to the LSST pointing model *kraken_2026*. The initial analysis yielded only three TCOs to be picked up by the Moving Object Processing System. A study to increase the number of identified detections by alternative means was performed. A sample of objects with exiguous number of detections was selected, and orbital linking together with initial orbital determination and subsequent assessment of resulting geocentric scores was performed. In the best case scenario, an improvement by an order of magnitude in the detection of TCOs can be achieved through alternative methods compared to the baseline treatment. Finally, the confusion between TCOs and various other trailed sources has been discussed.

The author had the main responsibility of writing the paper, drew Figures 2-9, provided the initial condition simulations and performed analysis on the survey simulation provided by Lynne Jones.

Paper IV

Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., Brown A. G. A. and 621 co-authors, including **Fedorets, G.** (2016). The Gaia mission. *Astronomy & Astrophysics* **595** A1.

Paper IV is a post-launch overview of ESA's Gaia mission, published together with Gaia Data Release 1. Gaia is a spaceborne, primarily astrometric mission, with complementary photometric and spectroscopic capabilities. Its primary goal is to construct a three-dimensional model of a billion stars in the Milky way galaxy; however, Gaia is also a prominent synoptic survey. The article discusses the scientific goals of Gaia, including implications for the Solar System science; describes the spacecraft and payload, including the astrometric measurement principle; gives an overview of the launch and commissioning phase. The article then describes the science operations of Gaia; one part of which is daily processing of newly discovered Solar System objects and distributing alerts to follow-up observers. The article continues with the depiction of data processing and analysis of Gaia. In the end, an estimate of end-of-mission performance in terms of astrometry, photometry, spectroscopy as well as the survey coverage and completeness is given.

The author is a member of the Gaia Collaboration through the Data Processing and Analysis Consortium of Gaia, and has been responsible for maintaining and developing the orbital inversion software included in the pipeline for the daily processing of newly discovered asteroids. This pipeline produces alerts for follow-up observers.

Paper V

Muinonen, K., **Fedorets, G.**, Pentikäinen, H., Pieniluoma, T., Oszkiewicz, D., Granvik, M., Virtanen, J., Tanga, P., Mignard, F., Berthier, J., Dell'Oro, A., Carry, B. & Thuillot, W. (2016). Asteroid orbits with Gaia astrometry using random-walk statistical ranging. *Planetary and Space Science* **123** 95 – 100.

Paper V introduces a new orbital inversion method called random-walk ranging. The method has been specifically designed for the Gaia mission to combine robustness and fast computation time of its predecessors. The method is implemented in the daily processing chain of new asteroid discoveries (Paper VI). The article reviews the statistical inversion theory for orbit determination, eventually deriving the random-walk ranging from statistical and Markov-chain Monte Carlo ranging methods. The software implementation is introduced. The method is validated through calculations of initial orbits for two different asteroids. The method is compared to other similar orbit computation methods.

The author implemented and validated the method software-wise, wrote sections 2.4.and 3 and part of section 4 of the manuscript, and performed all calculations and drew all the plots.

Paper VI

Tanga, P., Mignard, F., Dell'Oro, A., Muinonen, K., Pauwels, T., Thuillot, W., Berthier, J., Cellino, A., Hestroffer, D., Petit, J.-M., Carry, B., David, P., Delbò, M., **Fedorets, G.**, Galluccio, L., Granvik, M., Ordenovic, C. & Pentikäinen, H. (2016). The daily processing of asteroid observations by Gaia. *Planetary and Space Science* **123** 87 – 94.

Paper VI describes the short-term processing of data for newly discovered asteroids with Gaia. The article begins with the technical description of Gaia, including its optics, scanning law, and data processing, and the implementation of the data processing chain. The article then describes the tool used to predict the detection of known Solar System objects with Gaia. The data flow of the daily processing pipeline for asteroids begins with the identification of moving targets in Gaia's fields of view, and cross-matching them with known asteroids in the data flow. The asteroid signal is then analysed, with the mean position and flux measured for each CCD.

The CCD pixel coordinates are then translated into astrometric positions, which are combined into transits, and threaded into bundles. The initial orbit determination is performed for bundles with random-walk ranging, described in Paper V. Based on initial orbit determination, ephemeris for follow-up observations are calculated and distributed to follow-up observers.

The author participated in writing section 6 of the article, and produced Figure 5, and commented overall on the manuscript.

Paper VII

Fedorets, G., Muinonen, K., Pauwels, T., Granvik, M., Tanga, P., Virtanen, J., Berthier, J., Carry, B., David, P., Dell'Oro, A., Mignard, F., Petit, J.-M., Spoto, F. & Thuillot, W. (2018). Optimizing asteroid orbit computation for Gaia with normal points. *Astronomy & Astrophysics* **620** A101.

Paper VII introduces the normal-point treatment of the short-term processing of Gaia. Initial results from the short-term processing showed that the ephemeris predictions for follow-up observers are much larger than has been expected. The problem has been tracked down to the fact that Gaia has rather large systematic errors in its short-term processing (Paper VI). The daily processing chain is introduced, Gaia's error model is described, and the normal-point treatment is introduced, effectively transforming each Gaia transit into a single observation. The main effect of this was combining the systematic errors of within-transit observations into a single, reduced systematic error. The article further reviews various ranging-based orbital methods, including random-walk ranging (Paper V). The developed approach is validated with Gaia data with different number of observations. The prediction ephemeris cloud shrank into a fraction of the previous value. In the Keplerian phase space, a typical outcome is the disappearance of close-by low-weight solutions with outstanding values of i and Ω, that are primary contributors to the initial wide distributions of ephemeris predictions. The number of necessary sample orbits is also assessed. The normal-point method has implications beyond Gaia, and is applicable to all observations with systematic errors in stellar catalogues.

The author implemented the method software-wise, performed all calculations and drew all the plots, and had the main responsibility of writing the paper, except for sections 2.2-2.5, which were written by Karri Muinonen.

6 Concluding remarks

The present thesis investigates exiguous asteroid astrometry in the context of synoptic surveys. Two different cases of such data were studied: NESes (Papers I-III), and new asteroid discoveries with Gaia (Papers IV-VII).

Exiguous data is important in revealing new populations for statistical studies in asteroid sciences – as is the case of LSST with TCOs. With the enormous fully-automated data flow of future surveys, exiguous data may be overlooked as of secondary importance. However, objects with exiguous data are the ones that open new avenues of research and should not be overlooked. Therefore, the follow-up for discovered objects with exiguous data is essential.

What makes NESes unique among newly observable populations is that they are natural objects absolutely closest to Earth. Usually, the horizons of observations are expanded through detections of more distant objects. NESes are a class of objects that are expected to be characterized with the generation of observational facilities emerging in the 2020s. The combination of LSST and a global network of follow-up facilities will enable to characterise TCOs and perhaps also TCFs, and provide a stepping stone for their in situ investigation and resource utilisation.

TCOs are small in size, and, even with such progressive instrument as LSST, they lay on the discovery threshold. Even so, they are outstanding sample return mission targets in terms of their Δv. In the case of sample return from a TCO, there is a genuine possibility for a leap in the size of a sample returned from an asteroid. Retrieving an entire one-metre sized body, similar to boulders on the surface of rubble-pile asteroids such as (162173) Ryugu, would enable characterizing an entire monolithic asteroid completely for the first time. Like for many other fields, spaceflight benefits from the robustness of a stepwise approach, especially with missions to objects which require years or decades of transfer. With NESes, which are in the vicinity of the Earth and are constantly replenished, there is however room for daring attempts for asteroid space missions on short timescales.

The Gaia catalogue will essentially reduce the present stellar catalogue errors to the ten-microarcsecond level. The error of asteroid positions will be on the order of hundreds of microarcseconds. The accuracy of Gaia is unprecedented. Therefore, the Gaia catalogue will supersede all existing catalogues in accuracy, and will be beneficial for establishing astrometric accuracy for other survey programmes such as LSST. A general operating mode of survey programmes is to distribute precise data through data releases after meticulous calibration, while the immediate data releases for alerts are of significantly poorer quality. Especially in cases of quick-look quality of data, the sources of systematic errors should be recognised. The normal-point approach is a valid method to reduce the effect of systematic errors on astrometric accuracy of asteroids. The normal-point approach is not restricted exclusively to alerts, but can be used for any type of astrometric data.

In the era of 10-m-class telescopes being the largest ground-based observatories, dedicated survey telescopes were of 2-m-classes. With shifting of the state-of-the-art instrumentation to the 35-metre class telescopes, and the commissioning of the 8-m LSST, there is a vast seam of knowledge on asteroids to be unveiled in the next decade. Based on the recent incremental technological advancements, in the following 50 years one might perhaps expect a JWST-sized Gaia-type space mission and a 30-metre LSST-type facility. Optimally, future large facilities should include a global network of smaller dedicated follow-up facilities to work under auspices of the same project to ensure the due follow-up for objects requiring immediate follow-up observations. The larger survey telescope will have a synoptic approach while the smaller telescopes will specialise in certain areas of follow-up.

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