Impact Monitoring of Near-Earth Objects: review of classical results and new tools for the optimized follow-up of imminent impactors

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The solar system is populated with, other than planets, a wide variety of minor bodies, the majority of which is represented by asteroids. Most of their orbits are comprised between those of Mars and Jupiter, thus forming a population named **Main Belt**. However, some asteroids can run on trajectories that come close to, or even intersect, the orbit of the Earth. These objects are known as **Near Earth Asteroids (NEAs)** or **Near Earth Objects (NEOs)** and may entail a risk of collision with our planet. Predicting the occurrence of such collisions as early as possible, is the task of **Impact Monitoring**.

Dedicated algorithms are in charge of orbit determination and risk assessment for any detected NEO, but their efficiency is limited in cases in which the object has been observed for a short period of time, as is the case with newly discovered asteroids and, more worryingly, **imminent impactors**: objects due to hit the Earth, detected only a few days or hours in advance of impacts (10). This timespan might be too short to take any effective safety countermeasure. For this reason, an improvement of current observation capabilities is necessary and, in this frame, the **NEOSTEL Fly-Eye telescope** is being realized (3).

The telescope, to be installed at Monte Mufara (Palermo, Italy), is expected to increase the number of NEOs and, consequently, imminent impactors detected per year (7), thus requiring an improvement of the methods and algorithms used to handle such cases.

Moreover, when few observations are available, the uncertainty associated to the orbit is large and rapid follow-up is necessary to confirm or dismiss the possibility of an impact.

In this scenario, the thesis work focuses on the development and testing of new Impact Monitoring tools dedicated to the observers, aiming to facilitate the planning of follow-up observations of imminent impactors.

The software we used and into which we propose to implement the new features is **OrbFit**: a multipurpose code able to perform orbit determination and Impact Monitoring computations.

This thesis work consists of four chapters, the contents of which are here briefly summarised:

- **Chapter 1** gives background information about the NEO environment, briefly reviewing the dynamical and physical characteristics of the population (2). After a description of NEO observation techniques and main surveys, the Fly-Eye telescope is introduced, together with some predictions about its expected contribution to the Impact Monitoring field. Basic concepts about Orbit Determination and Impact Monitoring are briefly presented.

- **Chapter 2** describes in detail the already existent mathematical tools used in the phases of orbit calculation and risk assessment. In particular, we start with some useful definitions and reference frames, presenting the Minimum Orbital Intersection Distance (MOID) as a measure of the distance between the orbits of a NEO and the Earth, regardless of the positions that the objects occupy on them (9). We then proceed describing the use of the **Confidence Region (CR)**, the set of all possible orbits statistically compatible with a given set of observations. The sampling of a one-dimensional representative of the CR, the **Line Of Variations (LOV)**, results in the generation of a swarm of Virtual Asteroids (VAs). Each VA is then propagated in time, in search for intersections between its trajectory and the cross section of the Earth. If they are found, the relative VA is recorded as a Virtual Impactor (VI), associated to a certain Impact Probability (5). We then show how in the case of imminent impactors the LOV sampling method is inadequate (8) and the generation of VAs is better conducted over an **Admissible Region (AR)**, by sampling the **Manifold Of Variations (MOV)**, that is the two-dimensional manifold in the plane of range-range rate, comprising all the orbits compatible with a given set of observations (6). Finally, the chapter reviews the algorithms previously and currently employed for Impact Monitoring (4), highlighting the difference between "classical" Impact Monitoring and the imminent impactors case. The **OrbFit** software and its features are then presented (1).

- **Chapter 3** represents the core of our work, presenting the new tools that this thesis proposes to introduce to facilitate the follow up of newly discovered NEOs.
  The first tool computes the MOID of a given object and gives its graphical representation on the Admissible Region plane, allowing to identify at first glance the groups of VAs that might lead to a close encounter with the Earth. A fit of the points with near-zero MOID allows to draw a MOID=0 line that, if close enough to the nominal solution, shows if an impact is possible.
  The second tool computes the remaining visibility time for a given object from an observatory of choice.
  Combining the outputs of the two tools, we can select the objects for which to solicit immediate follow-up, before they collide with our planet or become unobservable and, possibly, lost with a nonzero probability of impacting at a later close approach. We illustrate our results with some examples of how the tools perform on real-life cases.

- **Chapter 4** summarizes the results obtained, highlighting advantages and faults of the new tools. Finally, further development possibilities are proposed, both for our tools and Impact Monitoring algorithms in general.

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