Impact Monitoring of Near-Earth Objects: old algorithms and new challenges

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This thesis presents a review of the theory and of the techniques concerning the *impact monitoring* of Near-Earth Objects (NEOs). The NEOs population includes asteroids with a heliocentric orbit and comets both having perihelion distances $q \leq 1.3$ AU, and aphelion distances $Q \geq 0.983$ AU. An asteroid that has just been discovered has a strongly undetermined orbit, being weakly constrained by the few available astrometric observations, and there is a set of possible orbits, all compatible with the observations, forming a *confidence region* in the 6-dimensional orbital elements space. This region can be sampled by a set of *Virtual Asteroids* (VAs), that are orbits representative of the entire region; among them there is the real orbit but we do not know which one. Thus, it might be the case that an impact on the Earth in the near future cannot be excluded. The goal of impact monitoring is to investigate whether an asteroid may have an impact on the Earth in the future, that is to establish whether the confidence region contains some *Virtual Impactors* (VIs), a subset of the initial conditions leading to a collision with the Earth. A crucial issue is to be able to identify hazardous cases as soon as new objects are discovered or as new observations are added to prior discoveries; since a significant amount of new observations are submitted every day, this activity requires an automated system scanning continually the NEA (Near-Earth Asteroid) catalog. This has been achieved by CLOMON2 and Sentry, two independent impact monitoring systems that are operational at the University of Pisa (since 1999) and at NASA Jet Propulsion Laboratory (since 2002), respectively. During the time span over which observations are obtained, CLOMON2 and Sentry outcomes, eventually with the announcement that some asteroid has the possibility of impacting, are published on the web; in particular, CLOMON2 results are published on the on-line information system NEODyS[1]. These two systems, whose output is carefully compared, now guarantee that the potentially dangerous objects are identified very early and followed up. Both the systems generate VAs by applying a 1-dimensional sampling method of the confidence region based upon the *Line Of Variations* (LOV), that is a differentiable curve representing a kind of “spine” of the confidence region. The LOV method is very useful when the confidence region is elongated and thin, but this is not the case when the observed arc is very short ($\leq 1°$). When the set of observations of an object covers only a very short arc, the confidence region results to be wide in at least two directions; thus the LOV is not representative of the entire confidence region and its definition strongly depends upon the coordinates and units used. In this case, both CLOMON2 and Sentry do not perform very well. Therefore, it has been proposed a different technique, based upon the idea of changing the geometric object used in the sampling method and switching to a sampling by surfaces of the *Admissible Region* (AR), that is a 2-dimensional manifold containing orbits compatible with the observations. By following this approach, systematic ranging methods have been developed, with the aim to optimally analyse objects having only short observed arcs available. Among their various applications, these methods are also used in detecting when a small asteroid just discovered may be an *imminent impactor*. In particular, softwares based upon such techniques have been successful in predicting the impact on Earth of small asteroid 2018 LA on June 2, 2018, that collided shortly after being discovered.

This thesis work has been carried out thanks to a short university internship made at spin-off company SpaceDyS[2], giving the opportunity to study OrbFit software's code (upon which is based the system CLOMON2) and to analyse its output files. SpaceDyS is currently working to the development of an impact monitoring software, called AstOD, in the context of a migration of the NEODyS activity at European Space Agency ESRIN; thus, it was also possible to make a theoretical comparison between the procedures implemented in OrbFit and AstOD. Moreover, we could also analyse the outcomes of the follow up activity of asteroid 2018 LA that has been obtained by using a software based upon a systematic ranging technique.

In the first part of this thesis we summarize the main theoretical tools developed to set up an impact monitoring procedure, as it has been implemented in CLOMON2 and Sentry. In Chapter 1 we present the

[1] Available at `https://newton.dm.unipi.it/neodys/`.

[2] Space Dynamics Services s.r.l., via M. Giuntini, Navacchio di Cascina, Pisa, Italy. Website: `http://www.spacedys.com/it/`.

Öpik's theory of close encounters (Öpik [8]) and some specific tools and methods aiming to analyse a close approach of an asteroid to the Earth (Milani and Valsecchi [7]). Then we briefly illustrate the notions of *resonant returns* and *keyholes* (Valsecchi et al. [12]) and their role in the framework of impact monitoring. In Chapter 2 we show several definitions of the LOV with a uniform step-size sampling method and discuss the issue of selecting a metric for the LOV parameterization (Milani et al. [6], Milani and Gronchi [5] chapter 10). In Chapter 3 we illustrate an overview of the whole procedure of impact monitoring as implemented in CLOMON2 and Sentry (Tommei [10]), describing the mathematical theory applied in the development of these systems and focusing on certain methods recently introduced in CLOMON2 (Del Vigna et al. [2]). In the last part of the chapter we will provide a description of the implementation of such procedures in OrbFit's code and of the structure of its output files, according to the analysis work done during the internship; we also outline the main theoretical characteristics of the software AstOD.

In the second part of the thesis we illustrate recently developed techniques to deal with the issue of imminent impactors detection. In Chapter 4 we discuss the problem of short observed arcs, namely *Too Short Arcs* (TSAs) and *Very Short Arcs* (VSAs), introducing the Admissible Region as a tool to obtain a set of orbits compatible with the observations. We shall present two techniques (proposed by Tommei [11], [10]) to sample the AR in VAs in the case of TSAs and VSAs. In Chapter 5 we describe two different systematic ranging methods (Farnocchia et al [4], Spoto et al. [9]) to sample the AR; such techniques have been implemented in two services (Scout and NEOScan) that scan the Minor Planet Center NEO Confirmation Page[3] (NEOCP) every two minutes, determining whether an observed object is a NEO, computing its *impact probability*, and also assigning a priority level to the follow up activity of the object. Lastly, we show some examples of application of NEOScan. These services have been proved to obtain good results and they constitute fundamental tools in detecting whether a small just discovered asteroid may be an imminent impactor. In Chapter 6 we describe the case of the small asteroid 2018 LA, that we analysed during the internship. We show the results of the software implemented upon the systematic ranging method proposed by Spoto et al. ([9]) (which is the kernel of the service NEOScan) obtained during the follow up of the object. Furthermore, we present a semilinear method to predict the *Impact Corridor* (Del Vigna [1], Dimare et al. [3]), that is a stripe going from a chosen altitude in the atmosphere to the Earth's surface containing possible impact locations; finally, we show the result, by applying this technique, of the prediction of the impact corridor of 2018 LA, discussing how the result is consistent with the actual impact location.

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[3] It is a "catalog" of observed objects, available at `http://www.minorplanetcenter.net/iau/NEO/toconfirm_tabular.html`.