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On protecting the planet against cosmic attack: Ultrafast real-time estimate of the asteroid's radial velocity

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ABSTRACT

A new method for the line-of-sight velocity estimation of a high-speed near-Earth object (asteroid, meteorite) is suggested. The method is based on the use of fractional, one-half order derivative of a Doppler signal. The algorithm suggested is much simpler and more economical than the classical one, and it appears preferable for use in orbital weapon systems of threat response. Application of fractional differentiation to quick evaluation of mean frequency location of the reflected Doppler signal is justified. The method allows an assessment of the mean frequency in the time domain without spectral analysis. An algorithm structure for the real-time estimation is presented. The velocity resolution estimates are made for typical asteroids in the X-band. It is shown that the wait time can be shortened by orders of magnitude compared with similar value in the case of a standard spectral processing.

1. Introduction

The eventful month between mid-February and mid-March 2013 reminded the mankind that the asteroid-comet threat is real. 'Chebarkul' super-bolide which exploded on February 15, 2013 over the densely populated region of Chelyabinsk caused damage of buildings and injuries of people. Close flybys of two potentially hazardous asteroids 2012 DA14 [1] and 2013ET [2] at 0.07 and 2.5 lunar distances from Earth, 44 and 100 m in diameter respectively, both able to ruin a city, also received extensive coverage in mass-media. Besides, the latter one was discovered just 6 days before its closest approach to Earth while the Chebarkul meteorite was only recorded after it had entered the Earth atmosphere.

These events confirmed a universal truth: with the means of near-Earth space scanning what they are now, a hazardous near-Earth object (NEO) can remain undetected on the distant approaches to Earth, leaving very little time to react. Thus the long discussed problem of protecting the Earth from cosmic threats requires a quick transition to the phase of practical realization.

Protecting the planet from cosmic threats means detection of hazardous NEOs, measuring their parameters of motion, trajectory calculation, and their destruction or, at least, prompt alert of the national services for the population protection in the threatened area.

Prior works propose implementing cosmic threat protection through deployment of detection and destruction systems on the near-Earth orbits [3–5]. The combat platforms deployment on the geostationary orbit is advantageous for a variety of reasons: (i) ground station contact can be maintained permanently by directional antennae and (ii) an asteroid's approach in the eclipse plane is the most expected; the angle between geostationary orbit plane and eclipse (23°) is not large enough to obstruct operation of the communications and targeting facilities.

At the most dangerous speeds of 30–60 km/s an asteroid's approach time from the Lunar orbit to the geostationary orbit is about 100–200 min. In this scenario the

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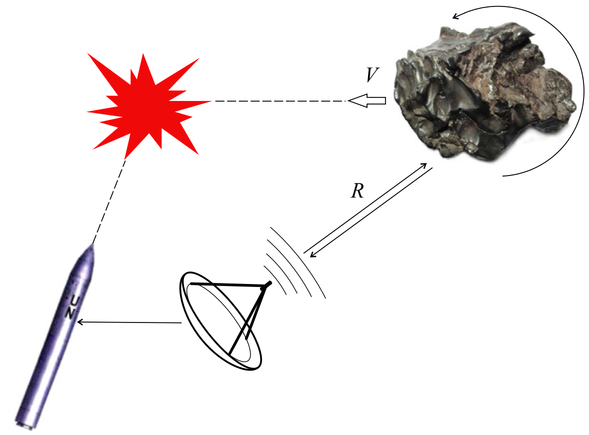

Fig. 1. A scheme of the asteroid-comet threat counteraction at the final stage.

time for location, selection, and maneuver is much limited and the success of action (to eliminate the threat) depends on the precision of aim.

The most reliable and accurate information can be obtained from radiolocation measurements of the asteroid's distance and radial velocity. They allow of robust prediction of motion of the hazardous celestial body [6,7]. Besides, the radiolocation method is much easier in application in the near-Earth space directly.

When determining the coordinates of the cosmic object one needs a quick, accurate prediction of its trajectory so as to calculate the kill point. It is obvious that at the terminal phase of target approach parameters of the asteroid motion must be measured near-real-time by the radar system based on the weapon system (e.g. missile) when homing (Fig. 1). Since the distance between a missile and an asteroid is relatively small at the final stage of self-homing (tens or hundreds of kilometers), there are no specific requirements for the operational range of the radar system. At such a large relative velocity ($\gtrsim 30$ km/s against ~ 10 km/s), even a minor inaccuracy can disrupt the difference between the weapon system and the asteroid target destruction. Under the circumstances the cost of errors increases manifold and fidelity requirements should be maximized.

The usual trajectory prediction is done by measuring the object's velocity through analyzing the Doppler frequency shift of the reflected radar signal. Measuring Doppler frequency accurately and promptly ensures an effective cosmic shield.

When different points of the object that form the reflected signal are moving at different velocities say, upon the object's rotation, the reflected signal can have a wide spectrum of Doppler frequencies [8], which correspond to the spectrum of velocities of reflecting points on the object's surface. In such a case the gravity center of the Doppler signal's[1] energy spectrum is commonly used. This parameter stably corresponds to the center mass motion of the moving object.

In the present paper a the use of original algorithm of NEO's high radial velocity estimate within the time of the Doppler signal arrival is proposed: this algorithm allows an economical use of the timing budget and computational resources of the cosmic shield system when making a trajectory prediction. The authors hope that their contribution to asteroid-comet threats protection will permit, in a small way, a reduction in the probability of hazards to life on the Earth in the foreseeable future.

2. Evaluation of the mean frequency of the Doppler signal spectrum

Evaluation of the spectrum gravity center (mean frequency) ω_0 assumes calculation of the energetic spectrum, that is, spectral processing of the signal $x(t)$, which requires bulk memory and, above all, a significant amount of processing time. The latter should be considered unacceptable on tactical grounds with the problem in hand.

The moments method is widely used in the signal theory for evaluation of the frequency spectrum parameters [9,10]. According to this the mean frequency of the signal's $x(t)$ spectrum on a positive semiaxis is defined as a gravity center ω_0 of its energetic spectrum $E(\omega)$:

$$\omega_0 = \int_0^\infty \omega W(\omega)\, d\omega = \frac{\int_0^\infty \omega E(\omega)\, d\omega}{\int_0^\infty E(\omega)\, d\omega}, \tag{1}$$

where $E(\omega) = |\dot{S}(\omega)|^2$; $\dot{S}(\omega) = F[x(t)]$ is a spectrum density of the amplitude of the signal which is limited by the observation interval $[0, T]$. Since the weighting function

$$W(\omega) = \frac{E(\omega)}{\int_0^\infty E(\omega)\, d\omega} \tag{2}$$

makes sense of the a posteriori distribution density in the spectrum of the received signal, the estimate (1) proves to be optimal involving additive noise [11]. This circumstance is justified by the fact that the gravity center of the Doppler frequency spectrum (Fig. 2) is determined by the velocity of the geometrical center of the reflecting object

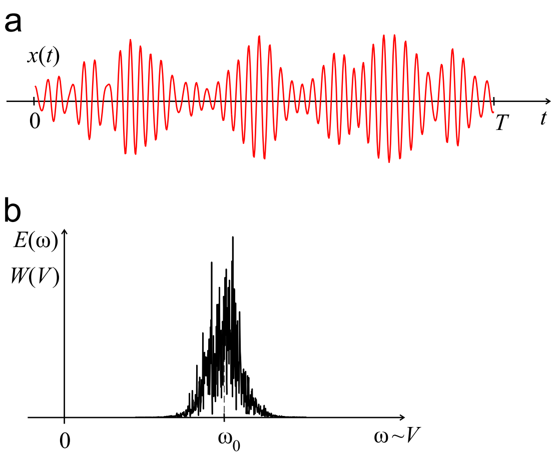

Fig. 2. The Doppler signal (a) and its energy spectrum (b).

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[1] In radiolocation the Doppler signal means an oscillation achieved as a result of detecting the signal reflected by the target by means of a synchronous detector. In this case we assume that the carrier frequency of the signal emitted by the radar is used as the reference oscillation.