PDC2025
Stellenbosch, Cape Town, South Africa

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☐ **Earth Impact Effects & Consequences**

Multi-Parameter Monitoring of the Potential Impact of the Exercise Asteroid 2024 PDC25

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Keywords: *Asteroid Threat Exercise, Earth Impact Effects, Impact Monitoring*

Abstract

Regarding the most recent asteroid mitigation exercise, we point out that if the mitigation efforts do not succeed to alter the trajectory of (the fictitious object) 2024PDC25, the asteroid will reach the surface of the Earth along the border between the Democratic Republic of the Congo in the north and Angola in the south, possibly depositing up to 250 megatons (TNT equivalent) of energy and creating a crater of about 3 km in diameter. If this happens it would be of obvious interest to observe this impact in as much detail as possible. In this respect we propose to populate the impact area with suitable sensors and probes, ranging from drones in various altitudes in the atmosphere to the surface and below. The goal of this paper is to sketch out a strategy for these observations in terms of requirements, capabilities, feasibility, and data sampling and storage. Suggestions will be made as to the type of equipment, transmission frequencies and bandwidth.

The expected impact-related phenomena include electromagnetic interactions with the atmosphere and with the target material; pressure waves and acoustics in the air and on the ground; events in the plasma and in the fireball, observable with suitable spectrometers. Seismic data can be combined with data from the UN Comprehensive Test Ban Treaty Organization (CTBTO). High precision Global Navigation Satellite System (GNSS) data, using differential signal strategies, could also be useful, as are detailed satellite monitoring data, including using radar and radio signal monitoring instrumentation, which would also be of benefit. After an impact, an effort to reach the impact site to study the distribution of rock types and take a variety of samples,

including monitoring the temperature development of the crater fill rock and other parameters, would be advantageous.

The data can be collected in a suitable data base and combined with data obtained from satellites and other remote sensing platforms. In this manner a full digital model of the impact event can be constructed.

Introduction and Background

Interactions of small of asteroids (meteoroids) with the Earth's atmosphere and surface have been observed in the past, albeit in less than optimal conditions. These events, in the form of airbursts happened spontaneously and surprisingly. Suitable observing equipment was not near the event site, nor was it optimized to best register the event. In the case of the Chelyabinsk event in 2013 (Ref. 1), for instance, data were elaborately collected from videos taken by dashboard cameras, which had been uploaded to social networks. While in the end the event was relatively well documented it was very tedious to obtain reliable data. For Tunguska, which happened in 1908 remote data (such as air pressure measurements) existed, but the very remote site itself was only reached many years after the event (Ref. 2). No actual crater-forming impact event has been observed yet, although several have happened in the past tens of thousands of years.

In the case of 2024PDC25 (which is the name of the current PDC simulation exercise object) we could be in a (hypothetical) position to pre-plan the observations. In the exercise there are of course attempts to deflect the object, but there is a possibility that this fails, or will be incomplete. Incomplete deflection of course changes the location of the impact site, which makes it important to design any monitoring equipment and the infrastructure such that it will be possible to deploy the observing assets in an efficient and rapid manner. The main point of this contribution is to use the hypothetical PDC asteroid threat exercise to describe an observation and monitoring concept for a relatively small scale impact event on Earth.

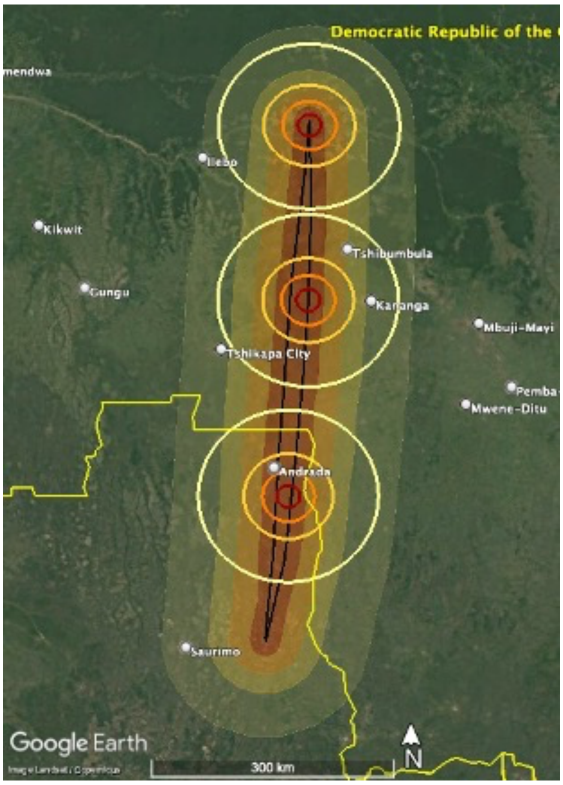

Fig.1. Current best estimate of the impact site of 2024PDC25 if unmitigated (Image: NASA JPL). (Ref. 3)

The observing strategy

We are proposing three grids of probes to observe the event.The first grid should be located on the surface. It should cover an area of about 100 by 100 kilometers, suitably spaced at around 10 kilometers around the most likely point of impact. This grid should consist of relatively conventional seismic and meteorological probes, augmented by suitable imaging devices.

There should be two other grids, consisting of drones, at an altitude of several kilometers. It would be attractive to aim for the altitudes of 5.5 km and 11 km, which are the isobars of half and a quarter of the surface air pressure, respectively. This will of course depend on the availability of drones that can reach the desired altitude.

Because about 100 ground stations and 200 drones might be required it is important that existing and easily available technology can be used. Fortunately, the recent advances in mobile communications and in the area of multi-purpose drones should make this possible and affordable. Some of the authors have experience with using such drones to carry payloads for the analysis of electro-magnetic (EM) environments.

In the case of an impending impact the deployment of the equipment must be carried our expeditiously. A suitable strategy could be to use 10 military trucks, carrying 10 observing stations each. Each truck would have to travel 100 km, planting an observing station every 10 km. It should be possible to do this in 24 hours or less, depending on terrain. If the terrain is prohibitive or the deployment of the observing stations turns out to be time consuming, trucks could be replaced by helicopters. Upon reaching the pre-defined position the ground station is firmly anchored in the substrate, in order to obtain best measurements and to withstand the blast wave. Next to it two drones should be placed. All batteries should be continuously charged through solar panels, that are to be deployed nearby.

At a suitable time before the predicted impact the ground stations should be activated and the drones should be launched in two waves. As the 3-D grid builds, it can be continuously monitored by one or several ground control centers.

There should be at least three ground control centers, suitably spaced around, and about 200 km distant from the impact site. We cannot assume that continuous direct communication with the control centers will be possible throughout the impact event, or that power remains available in the region. Therefore, communication has to be multiply redundant. This can easily be achieved by combining cellphone, internet, and satellite communication procedures. Close monitoring of the transmission signal strength and frequency shift can provide additional data with respect to the acceleration and the velocity of the drones as they experience the blast wave.

The ground probes

Seismic monitoring probes are available off-the-shelf. A monitoring station typically consists of several key components designed to detect and record ground motion caused by seismic activity. The main component is a seismometer to register the vibrations of the ground. They can detect a wide range of frequencies, from low-frequency seismic waves to high-frequency noise. Advanced models include broadband seismometers that provide detailed data across various seismic events.

A data logger collects and stores the data from the seismometer. It processes the incoming signals, filters noise, and formats the data for analysis. A Global Navigation Satellite System (GNSS) is included to provide precise location data and timing for the sequence of events. Accurate timing is crucial for analyzing the data and determining the location of seismic sources.

Fig 2: Compact seismic sensor. 180X120X100 mm (Ref. 4)

Complementing the seismic subsystem is a geophone which is used to detect ground motion and vibrations. The key features include sensors for horizontal and vertical vibrations in various frequency ranges, allowing them to detect different seismic wave types. Lower frequency geophones are suitable for detecting large-scale seismic events, while higher frequency models can capture finer details. For our application a combination of seismic sensor and geophone could be advantageous. As with the seismometer, the signals generated by the geophones are recorded by a data acquisition system, which passes the data on to the communication unit.

Fig. 3: Tri-axial geophone. Overall dimensions are 140X140X95 mm. (Ref. 5)

Another subsystem of the ground probe is the meteorological package. It consists of a compact device designed to measure and record atmospheric conditions. These stations are equipped with multiple sensors to measure different atmospheric parameters, such as a temperature sensor, which measures air temperature with high time resolution, using thermistors or thermocouples. Humidity Sensors monitor the relative humidity of the air, usually via capacitive or resistive sensors. A barometric pressure sensor and an anemometer for measuring wind speed and wind direction, complete the science package.

The ground monitoring stations may be powered by batteries, solar panels, or a combination of both to ensure continuous operation, especially in remote locations. Power generation with solar panels will not be possible after the impact event, either because of the attenuation of ambient light, or because of the physical destruction of the panels. For this reason, heavy duty batteries designed for rough environments are required.

The data from all subsystems are channeled into a data logger, that records measurements from all the sensors. This device stores data for later analysis, featuring memory storage and the ability to timestamp readings. The components should be ruggedized, so they can withstand, as much as possible, the effects of the impact.

A semi-independent unit is the all-sky camera, to capture panoramic images of the entire sky. Such a camera is equipped with an ultra-wide-angle lens, known as a fisheye lens, that allows to capture a 360-degree view of the sky in a single image. This feature is crucial for monitoring and triangulate the path of the asteroid through the atmosphere, and to record other events and atmospheric phenomena.

Fig 4: All-sky camera. Dimensions are 48X50X52 mm. (Ref. 6)

The camera typically uses high-resolution digital sensors to capture clear images. These sensors can be sensitive to different wavelengths of light, including visible and infrared, depending on the specific application. The images are usually stored on internal memory or external storage devices, allowing for long-term data collection.

All subsystems share the communication package, which allows for real-time data transmission to a central monitoring station or cloud-based service. It can include options such as satellite, cellular, or internet connectivity. In our particular case the communication must occur in real time and trough redundant paths. In addition, the data should be stored locally in case the data transmission does not work. Storage devices from surviving ground probes can be searched for and retrieved

The airborne probes

As the asteroid penetrates the atmosphere it creates a plasma trail, which is generated by friction and by adiabatic compression, the velocity of the body being a multiple of the speed of sound in the air. The airborne sensors carried by drones contain signal monitor payloads to measure echoes reflected by the plasma generated by the asteroid. The signals are emitted by (mobile) ground stations. The transmitters operate in sweep mode, scanning a range of frequencies, to allow the analysis of the properties of the asteroid and of the plasma trail.

In addition, radar sensors with 20 cm printed flat panel antennas on the airborne probes can be used to target the asteroid. Ranging in this challenging environment is based on the continuous wave (CW) principle with pseudo random sequences, establishing correlations between signal and echo. This system is capable of measuring distances very accurately, possibly yielding structures in the plasma trail as it decays.

The position of the airborne sensors is provided by GNSS receivers on board of the drones. Additional sensors comprise all-sky cameras with CCD sensors for the visible and IR spectrum a wideband spectrometer

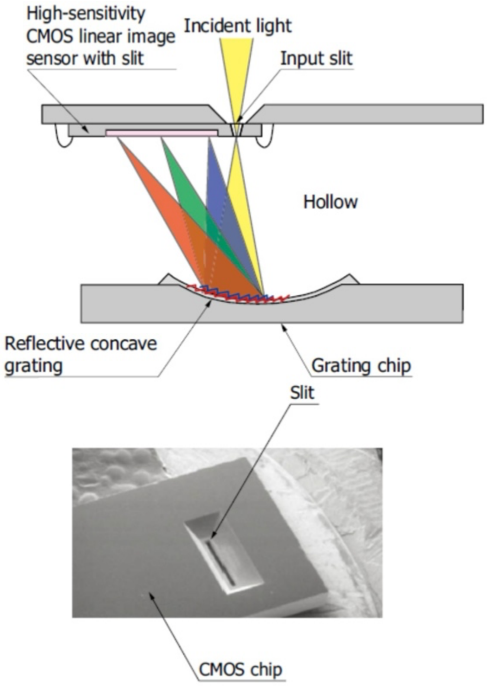

Fig. 5: Compact Wide Field Spectrometer concept (Ref. 7)

Fig. 6: Compact wide field spectrometers, size is about 20X13X10 mm (Ref. 8)

For real-time high-speed data transfer satellite communications can be used. The Medium Earth Orbit (MEO) constellation of Societé Europeenne des Satellites (SES, Luxemburg) has the advantage of wide coverage and high bandwidth in the Ka-band (approximately 27 to 40 Ghz), and convenient ground gateways (Ref. 9). The antennas are flat panels of approximately 20 cm in size. For redundancy, the low earth orbit (LEO) constellation by Eutelsat, OneWeb, is proposed, which operates in the Ku-band (approximately 15 Ghz). This approach has an advantage over Starlink, namely a lower of number of hand-overs between satellites and longer connect times per satellite. The accumulated data rate for this set-up is between 1 and 10 Gbit/s.

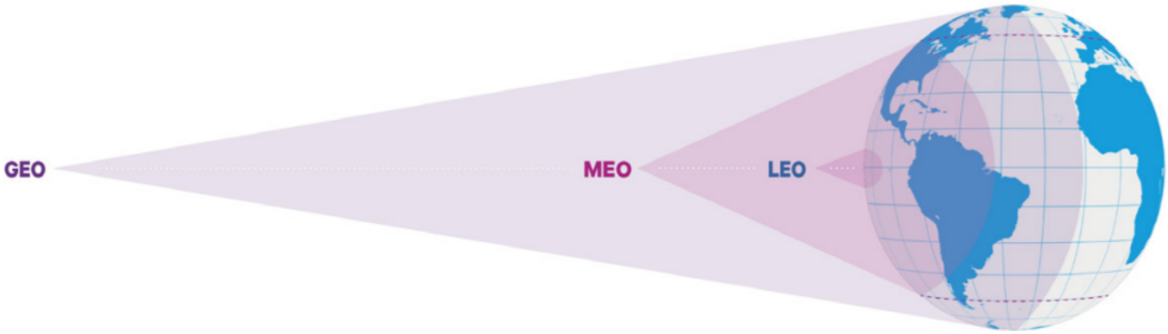

Fig 7: Respective coverage from different orbits (LEO- Low Earth Orbit, MEO- Medium Earth Orbit, GEO- Geostationary Earth Orbit). LEO not to scale.

Fig. 8: Drone with payload to monitor strength and direction of multi-wavelength electro-magnet signals. Dimensions of the detector enclosure are 200 by 200 by 100 mm. (Photo by the authors)

Data collection and analysis

Suitable software should be provided for data analysis and visualization. In a first step this software is used to visualize and interpret the seismic and the airborne data, and to generate high resolution observing logs. Ideally the observing probes on the ground and in the air can maintain a continuous data link with the monitoring stations. However, this will obviously not be the case for the probes closest to the impact, which might get physically destroyed, or their communication signals severely attenuated by the ion trail.

It is to be expected that there will be flyovers of the impact site as early as possible after the event, in an effort to observe the evolution of the impact crater. Surviving drones can be located using their GNSS trackers. Efforts can be made to retrieve them. Their data buffers can be read out to recover measurements, which did not get transmitted in time, and the data can be entered into the combined data base.

Other useful data can be gathered by monitoring suitable commercial radio stations in the vicinity of the impact site and to register the variations and interference of their signals. Satellite imagery should also be available. Finally, the impact should be registered by many seismic stations in Africa and elsewhere. In addition, the sensors of the United Nations Comprehensive Test Ban Treaty Organization (CTBTO) should register the event through their global network of highly sensitive seismometers and infrasound microphones.

The goal is to collect all available data and build a complete digital model of the event, which captures the spatially resolved details of the impact in three dimensions. This should allow to follow the evolution of the impact in time, including shockwave formation and various ephemeral events and structures in the plasma trail as it decays.

Conclusions

The concept described above is the kind of science program which, one hopes, will never be implemented. After all, should it come to an actual impact, there would be severe consequences, not only for the impact site, but also globally, with the severity depending on the actual location: economic uncertainty, cessation of agricultural and industry production, evacuation of a large number of people, etc. (Ref. 10). On the other hand, should the impact be unavoidable, it would be of obvious benefit to science to observe the event in the best possible manner.

Of course, the observing strategy sketched out in this contribution is rather generic and as such it is just the basis of an actual observing plan. Depending on external circumstances, the plan would have to be adapted: actual location of the impact, climatic conditions at the impact site, availability of transport, consumables and power, to mention just a few of the boundary conditions. It is also far from clear which organization could implement such a plan, as it requires considerable resources and a military-style organization and implementation protocol.

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