Deflecting an asteroid from an Earth impact trajectory requires only small velocity changes, typically of the order of microns per second, if done many years ahead of time. For this, a highly precise method of determining the need, magnitude, and direction of a deflection is required. Although the required precision can be achieved by much less accurate extended observations, an intrinsic resolution of $\mu$m/s permits the live monitoring of nongravitational orbit perturbations (Yarkovsky effect), and of a deflection effort itself. Here, it is proposed to deploy on the asteroid’s surface multiple radio units to form a phased array capable of measuring radial velocities relative to Earth to about $1 \mu$m/s and ranges to 5 m. The same technology can also be used for scientific applications such as very-long baseline radio astronomy, milli-Hertz gravitational wave detection, or mapping of the solar wind.

I. INTRODUCTION

Asteroid impacts on Earth are infrequent, but potentially devastating events. One example is (99942) Apophis, a 300-meter rock, which will miss Earth in 2029 by less than the orbital height of geostationary satellites. If, in this encounter, its center of gravity passes through the so-called keyhole – an imaginary, 600-meter wide region in space near Earth – then gravitational deflection will set it up for an impact in 2036 with an energy release similar to the explosion of Krakatoa in 1883. Making the asteroid miss the keyhole requires much less effort than avoiding the entire planet once the keyhole has been traversed: Up to three years before 2029, a velocity change $\Delta v < 1 \mu$m/s tangential to the orbit is sufficient to avoid the keyhole [1,2], but a $\Delta v$ of the order of cm/s is necessary for steering away from the entire planet after a keyhole passage. Therefore, a determination whether a deflection will be necessary should be done well before 2029. To obviate the need for an unnecessarily large deflection, the orbit should be measured to a precision commensurate with the required velocity change, i.e., $1 \mu$m/s. Passive radar can resolve velocities to a few cm/s and ranges to tens of meters, and only at distances much less than the orbital diameter of Earth and Apophis. A much higher accuracy can be achieved by use of a radio transponder traveling with or on the asteroid.

Placement and operation of a radio transponder on an asteroid is challenging in several ways, including (i) deliverable payload, (ii) power supply, (iii) unknown surface topography and composition, (iv) landing without bouncing off faster than the escape velocity of a few cm/s, (v) maintaining a directional link to Earth while the asteroid is rotating, (vi) degradation of radio signals due to interplanetary-plasma scintillations, and (vii) the space environment. The problem of landing would be irrelevant, and the power supply would be simpler with a transponder aboard a spacecraft orbiting/accompanying the asteroid, but transponders fixed to the asteroid surface can reach a much higher accuracy (see below). Therefore, the present proposal will concentrate on the latter approach.

II. DESIGN GOALS

First, to the accuracy: Doppler tracking of planetary probes has shown performance at the stipulated level, most recently $0.5 \mu$m/s for the gravitational-wave experiment [3] on Cassini currently orbiting Saturn. Orbital refinement techniques achieve this with much less precise individual measurements over an orbital period, but a high-precision technology permits live monitoring of a deflection maneuver, as well as of the Yarkovsky [4] effect (orbital perturbations due to radiation pressure). This would also be useful for using the Yarkovsky itself for deflection [5]. In addition to Doppler tracking, this proposal also aims for ranging at 5 m resolution, corresponding to $1 \mu$m/s over two months, about 20% of Apophis’ orbital period. These Doppler and ranging accuracies are stipulated for most of the asteroid’s orbit, except where the line of sight passes within 100 solar radii from the sun, and radio-signal degradation due to scintillations (see below) becomes too severe. This makes the maximum tracking distance 1.82 astronomical units (A.U.), i.e., $2.72 \cdot 10^8$ km.

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A radio transponder could be placed on the surface or aboard a companion spacecraft orbiting or tracking the asteroid. The latter option can be realized with proven spacecraft technology, but it cannot reach $\mu$m/s accuracy for the asteroid’s center of mass in a single measurement: due to the irregular shape and rotation of the asteroid, orbits are generally nonperiodic and unstable. Therefore, long averaging is necessary without orbit correction manoeuvres, but these would be required to prevent crashing or ejection. Active locking of a companion spacecraft to surface features of the asteroid using laser or radar ranging is also unlikely to be accurate to the $\mu$m/s level. Therefore, instantaneous high-precision measurements for live monitoring of deflections, or of the Yarkovsky effect, require a transponder on the asteroid’s surface.

III. DETAILS OF THE DESIGN

For reasonable power consumption, a directional antenna is required that compensates for the asteroid’s rotation. Using a tracking dish antenna on the low-gravity surface seems challenging. A much better approach is found in phased-array technology, where the phases of received and transmitted signals in a multitude of dipole antennae are controlled electronically without any mechanical motion for directionality through constructive interference. The phased array discussed here consists of 475 radio units grouped in 19 nodes of 25 each (Fig. 1). These numbers are somewhat arbitrary, and are meant only as an example. The nodes and the radio units within each node are linked together by a net of thin threads containing carbon fibers for mechanical strength, glass fibers for the distribution of a precise timing signal (for phasing) and digital communication, and metal wires for electric-power sharing. Each radio unit has 24 antennae for a total of 11400 for each of the frequencies used (see below). Each node contains a highly stable oscillator, one of which generates a reference frequency that is distributed over the glass-fiber network. Shortly before arrival, the transfer spacecraft aims for a collision with the asteroid at a velocity of about 0.1 m/s (roughly the escape velocity from the asteroid’s surface). As shown in Fig. 2 it then sequentially ejects 18 containers for the nodes, which are connected by carbon/metal/glass-fiber threads. To keep the fully deployed net spread out over about 800 meters, it is then spun up by gas jets to about one revolution per hour. Next, each container (including one in
FIG. 2: Deployment of the coarse web. A space vehicle (1) carries the array to the asteroid. It is comprised of three sections, each containing six slices. These are ejected in sequence (2-3-4) to deploy the web. After ejection of all slices, the entire web is made to rotate slowly to keep it stretched out (see text). Finally, each of the slices deploys a sub-web, as shown in fig. 3.

the remainder of the spacecraft) releases a thin plastic foil with attached radio units and inflates it to 50 m diameter by injecting gas into thin tubes (Fig. 3). Continuing on its collision course, the assembly wraps itself around the asteroid. After several slow-motion bounces that are restrained by the net, everything settles down in fixed random locations. Some damage is tolerable as it only leads to a slightly degraded performance (see below).

Next, Earth sends a radio signal sufficiently strong for reception without phasing (see below). As the asteroid rotates, the array compares the phases of this signal in each antenna to the local reference, and thus acquires the information necessary for phased-array operation at each of the frequencies used. This information is continually refined as the asteroid and Earth progress along their orbits.

The Doppler-tracking resolution is degraded by scintillations due to fluctuations of the radio refractive index n of the turbulent interplanetary plasma (solar wind). Extrapolating spacecraft-communication data [7] for a frequency of $\nu = 2.3$ GHz from 20 to 100 solar radii, and applying scaling $\nu^{-1.2}$ with $\nu^{-1.2}$, the spectral broadening due to scintillations of an 8-GHz signal at 100 solar radii is about 0.01 Hz. Ways to mitigate them are discussed in the literature on spacecraft-based gravitational-wave experiments [9, 10], using the dispersion $n^{-2}$ of n with multiple frequencies $\nu$ to measure, and then correct for the fluctuations. Here, frequencies of about 8 GHz and 16 GHz will be used (slightly offset in up- and downlink).

Doppler shifts are detected through phase shifts between ground and remote clocks, and a radial-velocity resolution of $\Delta v_r = 1\mu m/s$ requires the reference clocks to be stable to $\Delta v_r/c = 3 \cdot 10^{-15}$, where c is the speed of light. With a radio frequency of $\nu = 8$ GHz and a phase sensitivity of $s = 2\pi/100$ (3.5 degrees), this stability must be
duration must cover the initial ranging uncertainty of about 1 km, that is 3 every 1250 s for 1-

loss is about 20 MHz \[6\]. Here, the bit-time-bandwidth product of BT = 0.3 (standard in cell phones\[14\]), the signal bandwidth for a 5-meter resolution from the other. For a maximum operating distance of 1.82 AU at a frequency of 8 GHz, the signal is 2 tracking, one for ranging, and one for digital communication. Up- and downlink frequencies are slightly offset from used once the range is known better. The radio system thus uses four frequencies in each direction: two for Doppler

Glatter technique is proposed here \[6\] to make it easier to accommodate radio signals at two frequencies that fluctuate differently as they traverse the solar wind. With the above oscillator stability of \(10^{-13}\), the 1-\(\sigma\) walk-off of an 8-GHz signal is \(2\pi\) in 1250 s. Thus, to resolve the phase to \(s = 2\pi/100\), about 8 bits of digital data need to be transmitted every 1250 s for 1-\(\sigma\) certainty, and 10 bits for 4-\(\sigma\).

For ranging, Earth and the array transmit radio pulses to each other with a pseudo-random number (PRN) phase modulation similarly to GPS, and cross-correlate the received signals with the local ones. The array transmits the correlation result through the digital communication channel. With Gaussian Minimum-Shift Keying (GMSK) and a bit-time-bandwidth product of BT = 0.3 (standard in cell phones\[14\]), the signal bandwidth for a 5-meter resolution is about 20 MHz \[6\]. Here, \(\nu = 2.25\) GHz is chosen for the uplink, and \(\nu = 2.1\) GHz for downlink ranging. The pulse duration must cover the initial ranging uncertainty of about 1 km, that is 3 \(\mu\)s, but shorter PRN sequences may be used once the range is known better. The radio system thus uses four frequencies in each direction: two for Doppler tracking, one for ranging, and one for digital communication. Up- and downlink frequencies are slightly offset from each other to isolate the receivers at each end from the transmitters. Each of the up/down frequency pairs has 11400 antennae in the array.

The transmitter powers of the array and the ground station are determined by their mutual distance \(d\), the ground and array antenna gains \(G_g\) and \(G_a\), and the receiver sensitivities. On average, half of the 11400 antennae in the array are in view of the Earth at a given time, and their random orientations introduce another factor of 1/4, so \(G_a = 10\log(11400/8) = 31.5\) dB for all wavelengths. Signal diminution with distance is described by the free-space loss \(L = (4\pi d/l)^2\), i.e., the reciprocal solid angle subtended by a dipole antenna at one end of the radio link, as seen from the other. For a maximum operating distance of 1.82 AU at a frequency of 8 GHz, \(L = 10\log_{10} L = -279\) dB. Finally, the receiver is assumed to use a 70-meter dish antenna (gain \(G_g = 65\) dBi at 8 GHz) of the deep-space network \[15\]. The sum \(G_a + G_g + L\) gives a total transmission loss of -182.5 dB for all radio frequencies (\(L\) and \(G_g\) go opposite in frequency, \(G_a\) is frequency-independent). The receiver system noise temperature of the ground station is estimated \[16\] at 17 K, corresponding to a spectral power density of -186.3 dBm/Hz. For downlink Doppler

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FIG. 3: Ejection and unfolding of the sub-webs: 1: container opens, 2: folded plastic foil is ejected, 3: foil unfolds as gas is blown into tubes formed between two layers of the foil.
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maintained over the time \(\tau = (c/\Delta v_f)s/(2\pi\nu) = 375\) s. This exceeds the state of the art of 1 part in \(10^{-13}\) over 1000 s in spaceborne ultra-stable oscillators (USOs), but can be achieved with a coherent link \[11, 12\], where the uplink signal is used to phase-lock the space-borne oscillator from which the return signal is derived. Recently, the modified technique of noncoherent Doppler tracking \[13\] was used, where the spacecraft has a freely-running oscillator and transmits its phase slippage relative to the signal received from Earth through a digital communication channel. This latter technique is proposed here \[6\] to make it easier to accommodate radio signals at two frequencies that fluctuate differently as they traverse the solar wind. With the above oscillator stability of \(10^{-13}\), the 1-\(\sigma\) walk-off of an 8-GHz signal is \(2\pi\) in 1250 s. Thus, to resolve the phase to \(s = 2\pi/100\), about 8 bits of digital data need to be transmitted every 1250 s for 1-\(\sigma\) certainty, and 10 bits for 4-\(\sigma\).
FIG. 4: Left: The plastic foil of one node with 25 transponders sitting on it. Lower right: Closeup of the foil surrounding one transponder with microwave strip lines going out to the antennae, and a section of the plastic foil coated with a dielectric-mirror multilayer that reflects visible and near-infrared sunlight, but lets far infrared through. Upper right: Side view of the same. Sunlight is reflected off the coating, but far infrared heat radiation can escape into space. The transponder can thus radiate heat off to the ground surrounding it.

tracking, this noise power needs to be matched within a scintillation-broadened bandwidth of 0.01 Hz. With a 20-dB noise margin and a transmission loss of -182.5 dB, the array thus needs to output -3.8 dBm (0.4 mW) for each of the two radio frequencies. The design should foresee a slightly higher power to allow for a reduction in array gain due to a potential loss of radio units. For downlink ranging at 20-MHz bandwidth and 0-dB noise margin, the transmitter pulse power is 69 dBm (8.3 kW), to be shared among – on average – 5472 antennae. Each antenna driver thus outputs a peak power of about 1.5 W, i.e., about as much as a cell phone. With 3-µs-long ranging pulses transmitted once in 30 ms, the average power for ranging is 800 mW for the array, 3.4 mW per radio unit (assuming 235 of 475 being in view of Earth and active), and 140 µW per antenna. The lack of noise margin is compensated by repeated ranging pulses: 10000 pulses for a 20 dB margin taking 300 s define the time for one ranging measurement. Once the range is known to tens of meters, shorter PRNs can be used for lower average power or improved noise margin. Loss of some radio units does not disable ranging, but leads to an increase in the measurement time.

For the uplink, a higher transmitter power is available, but the receiver noise temperature is much higher (assumed here 1000 K, which is typical for cell phones). Thus, the ground station has to transmit at 60 times the downlink power, i.e., bursts of about 0.5 MW for ranging and a continuous signal of 24 MW for Doppler tracking. The initial-phasing signal has to be received without array gain ($G_a = 0$ dBi), and it needs to have a bandwidth given by the Doppler-shift uncertainty $\Delta \nu$ due to an initial velocity uncertainty $\Delta v$. For $\Delta v = 1$ m/s and $\nu = 8$ GHz, $\Delta \nu = 27$ Hz, and thus the ground station has to transmit at 1.6 kW for a noise margin of 20 dB.

Power is generated by radiation-tolerant, thin-film, amorphous-silicon solar cells deposited on the plastic foils of the nodes (see Fig. 4). This technology achieves a power of 2 kW per kg of solar-cell/substrate material for operation at 1 A.U. distance from the sun. Outside of the solar-cell areas, the foils have a broadband dielectric mirror coating to reflect visible and near-infrared sunlight, but let far-infrared escape. This reduces the temperature under the coating to well below the 321 K in black-body radiation equilibrium at 1 A.U. from the sun, so the radio unit can shed excess heat. At any given time, about half the radio units are in the sunlight and have to power themselves and the other half through the metal wires between and within the nodes, which are switched into rapidly varying configurations of
closed circuit loops containing power sources and sinks. At an efficiency of 10\%, the radio transmitters will consume an average power of 50 \text{ mW} (10 times (3.4 \text{ mW} for ranging, 2 \mu \text{W} for Doppler, 1.6 \text{ mW} for digital communication)), 50 \text{ mW} are needed for the on-board digital electronics, and 900 \text{ mW} for cooling radio units in the sunlight, so a radio unit in the sunlight needs to harvest 1 \text{ W} for itself. Radio units in the shade need 100 \text{ mW} for the electronics, 100 \text{ mW} power reserve for heating, and 100 \text{ mW} for internal power conversion losses. As estimated below, a sunlit radio unit then needs to harvest another 2.4 \text{ W} to power up to two units in the shade. With wires made of a high-strength aluminum alloy with a specific resistance of 2.9 \cdot 10^{-8} \Omega \text{ m} [6] and a cross section of 2.0 \cdot 10^{-8} \text{ m}^2 (250 wires of 10 \mu \text{m diameter, each), the wires have a resistance of 1.48 \Omega/\text{m.} For example, in a 1250-meter-long current loop with two sunlit nodes powering four in the shade (each with 25 radio units), a current of 100 \text{ mA} needs to run 50\% of the time to supply 30\text{ W} at a voltage drop of 600 \text{ V} (150 \text{ V} per node). There is an additional voltage drop of 185 \text{ V} in the wires. Therefore, each of the two sunlit nodes need to generate a voltage of 393 \text{ V} to power the loop. At 66\% power-conversion efficiency each sunlit node has to harvest about 60 \text{ W} for those in the shade, i.e., 2.4 \text{ W} per radio unit. For more detail, see ref. [6].

To determine the payload to be delivered to the asteroid, the following masses are estimated [6]: 47.5 kg for the 475 radio, 5 kg for the plastic foil of the 19 nodes (excluding the solar cells), 0.81 kg of solar cells (475*3.4 \text{ W} / (2 \text{ kW/kg})), 1.1 kg for 12 km of carbon/glass fiber/metal wires, 6 kg for the power-conversion electronics, master clocks and other infrastructure in the nodes, and 9.5 kg for the containers in which the nodes are stowed until they are deployed (Fig. 2). This brings the total array mass to about 70 kg. Another 80 kg can be estimated for the delivery spacecraft (structure, engines, tanks, etc.) for a mass \text{\(m_s = 150\)} kg to be delivered to the asteroid. An optimal transfer trajectory from low-earth orbit (LEO) to Apophis requires a total velocity change of \text{\(\Delta v = 7.71 \text{ km/s}\)} [6]. Applying the Tsiolkovsky rocket equation \text{\(m_f = m_s \exp(\Delta v/v_p)\)} for the total mass \text{\(m_f\)} at LEO, where \text{\(v_p\)} is the rocket exhaust velocity (3.07 \text{ km/s} for hydrazine thrusters), the mass to launch to LEO is about 1900 kg, which is well within the capabilities of commercial satellite launchers.

IV. OTHER POSSIBLE APPLICATIONS

Space-based phased arrays – based on asteroids, or floating freely – could also be used for other scientific applications, especially so if multiple ones are used. These applications make use of the capability of a phased array to transmit and receive simultaneously in different directions. One example is very-long-baseline (VLBI) radio astronomy [6] with baselines the size of Earth’s orbit. The arrays would maintain radio links with each other to distribute a master clock signal, and would simultaneously receive directionally from the radio source of interest. As the asteroids progress along their orbits, different Fourier components of the source’s angular distribution on the sky can be resolved to assemble an extremely high-resolution image, corresponding to the spacing between the asteroid-based receivers. Another possible application is in gravitational-wave detection at milli-Hertz frequencies, as is currently being done with the Cassini spacecraft [2]. Because this application requires a very high velocity accuracy, the arrays have to be based on asteroids to minimize their susceptibility to orbital perturbations due to the solar wind, the Yarkovsky effect, etc. With phased arrays based on several asteroids, multiple coherent links can be maintained simultaneously in different directions between asteroids to precisely locate a source [18]. Yet another possible application would be in the mapping of the solar wind by measuring the scintillations in radio links between several arrays. The transmitter power for the latter two applications may be estimated as before for the downlink in Doppler tracking, with the bandwidth again given by scintillations. However, the receiver temperature is now 1000 K (instead of 17 K), and the receiver antenna gain is 31.5 dBi (instead of 65 dBi). This requires an increase of the transmitter power by a factor of 1.1 \cdot 10^5 over the value of 0.4 \text{ mW} estimated before. Thus, for each link the array must transmit at 45 \text{ W}, and each of the about 200 to 250 radio units in view of the respective receiver must transmit about 200 \text{ mW. These scientific applications are not subject to the time constraints of a mission to track an asteroid before an impact or a keyhole passage. Therefore, lengthier but more energy-efficient transfer trajectories [19] are admissible, which will drastically reduce the mass to launch to LEO, and thus the mission cost.

V. SUMMARY

In summary, a way is proposed to precisely track the orbit of an asteroid by deploying a radio transponder on its surface, which establishes a two-frequency noncoherent link for Doppler tracking at 1 \mu m/s accuracy, returns broadband-modulated pulses for ranging to 5 m, and communicates digital data representing correlations between uplink and downlink Doppler and ranging signals. The transponder is a phased array of 11400 antennae for each of the four frequencies used, driven by 475 radio units. These are linked with each other by a net that serves the multiple purposes of enabling the landing maneuver in the low gravity of the asteroid, phasing the array, and sharing
solar-generated power. Due to a high degree of redundancy, the array can tolerate some damage, which will only lead to a slight reduction in antenna gain. The same phased-array technology can also be used for very-long-baseline radio astronomy or for gravitational-wave detection.

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