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On the Design Possibilities of a Non-Traditional Nuclear Device for Planetary Defense

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EXECUTIVE SUMMARY

In this paper, I argue for a new perspective on the design of nuclear explosive devices for planetary defense missions. At the time of writing, the placement of nuclear devices in space is explicitly banned under international law, and this is likely to be so for the foreseeable future. For this reason, I urge the design of new nuclear explosive designs specifically tailored to the planetary defense mission. Such designs could exploit the new operating environment of interplanetary space. For example, we can make reasonable estimates on the relative closing velocities of an asteroid with a space vehicle. We can then design the radar to be especially sensitive to such fast-moving bodies in the clutter-free environment that outer space provides. This narrowed design space allows us to optimize performance for the planetary defense mission alone, which would be a novel development.

While exploiting this new design environment, we ought to design a nuclear explosive device that, if used in a re-entry setting, would fail by design. This could be done by removing the ablative heat shield, or by changing the overall geometry of the device to be something that would exhibit abysmal performance on re-entry. This design choice is not intended to obviate international controls, but rather to work within those controls to produce a mission that could garner broad international support. Such work could be a boon to international diplomats looking to get to a “yes” vote on whether to authorize such nuclear devices at all.

The only use case for such a nuclear explosive device would take place well beyond the lunar orbit. This way, any gamma ray flux produced by the nuclear explosive would diminish as $1/r^2$ and would not pose a threat to Earth-orbiting satellites. Any nuclear detonation within the lunar orbit is not likely to produce the deflection required of a planetary defense mission, rendering such a scenario moot.

I offer a nominal trade study on how this freer design space can be used to improve the radar performance and fuzing of such a device. We are no longer concerned with a whole host of problems that are specific to re-entry environments. We should take the freedom afforded by this change of environment and use it to tailor a device that only has one job: to target and deflect near-earth objects.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
CST	Computer Simulation Technology®
EM	Electromagnetic
NED	Nuclear Explosive Device
NEO	Near-Earth Object
PEC	Perfect Electrical Conductor
RAM	Radar-Absorbing Material
RV	Re-Entry Vehicle
Rx	Receiver
SNR	Signal-to-Noise Ratio
SV	Space Vehicle
Tx	Transmitter
UN	United Nations

1. THE UN OUTER SPACE TREATY

The work of Sandia’s planetary defense researchers concerns the design and implementation of non-nuclear components of a nuclear explosive device (NED) for the purpose of an asteroid deflection mission. These activities will fulfill an emergency need in the event that a near-earth object (NEO) appears to be on a collision course with Earth, and if there is too little time (or the object is too massive) for a kinetic impactor to deflect it. Such a mission is fraught with diplomatic as well as technical complexity. At this time, the United States, as well as all other nuclear-armed states, are signatories to the United Nations Outer Space Treaty. Among its provisions, one clause states that “States shall not place nuclear weapons or other weapons of mass destruction in orbit or on celestial bodies or station them in outer space in any other manner.” [1] A straightforward reading of this text would prohibit the use of nuclear devices, even if such activity prevented the extinction of the human race. Much of the planetary defense work has presumed that either 1) a kinetic impactor will be sufficient to deflect an NEO, or 2) the international community would abstain from sanctioning the United States (or any other nuclear-armed benefactor) for violating the letter of international law. Some authors have argued that a legal framework exists for such a mission: if the UN Security Council adopts a binding resolution to use a NED for planetary defense, this may be sufficient [2]. That said, the objective of this study is not to circumvent international controls with loopholes. Rather, I seek to help diplomats and policymakers by giving them a tool that makes it easier to get to a “yes” vote.

The deflection of an asteroid in outer space – far enough away from Earth that communication between the device and earth-based command-and-control is impractical – presents a unique operating environment. Up to this point, we have considered how best to implement a conventional nuclear device design to deflect such an asteroid, and recommend engineering changes to that effect. We have also considered the nuclear deflection of comets as a *fait accompli*, since typical comets are far too large to be meaningfully deflected by kinetic impactors. There is also a non-negligible possibility of a Kuiper belt comet being jostled loose and entering the inner Solar System for the first time. Such an object would necessarily come with no observational history of its orbit, and we could have as little as a few months to deflect an object that is a kilometer in diameter. On the basis of this, we know there are plausible situations in which only a nuclear explosion will yield the desired deflection. But the thornier diplomatic issues raised by such a mission remain unaddressed.

I propose the following: instead of merely modifying a conventional nuclear device for a planetary defense mission, *we should design a nuclear explosive device that would be a poor candidate if used for belligerent purposes*. For example, in the priorities list of any nuclear device design, aerodynamic considerations usually come first, and electrical & radar considerations usually come close to last. There is good reason for this. If you have the most exquisitely designed radar system that money can buy, but the aerodynamics of the re-entry vehicle (RV) are so terrible that the whole system burns to a cinder on re-entry, then you have misallocated your resources. The shock, vibration, and aerodynamic priorities dictate the shape of the re-entry vehicle, and this in turn tightly constrains the trade space that radar designers can work with. Decades of flight tests have shown that radar engineers can still make highly successful radar systems within these confines.

When we transition to a space-only operating environment, we lose old problems (does the ablative heat shield protect the physics package?) and gain new ones (are the electronics sufficiently rad-hard to have high reliability for weeks, or even months, in outer space?). I believe that the trade space this new environment affords has yet to be exploited to its fullest potential. To that end, I suggest the following imperatives for a first-principles planetary defense mission design:

1. **Make the nuclear explosive device deliberately terrible as a re-entry vehicle.** Since we never need to operate at re-entry speeds in-atmosphere, we do not need to be bound to the conventional conical RV shape. We could design a space vehicle (SV) that ignored aerodynamics entirely and focused solely on delivering yield to a target in outer space. Such a design could conceivably be a beach ball (like the 1957 Sputnik satellite which burned up on re-entry), a cube, or even something irregular. Aside from capitalizing on the newfound freedom of this design, making the space vehicle something that would certainly burn up on re-entry would build faith with the international community that this device would not (and could not) be used for belligerent purposes.
2. **Take advantage of the unique mission space.** As alluded to above, the planetary defense mission offers unique challenges and opportunities. We must force ourselves outside the old rhythms of thinking about nuclear device design, and instead consider how the physics of an asteroid deflection mission naturally emphasize certain design decisions over others. Can we design a radar system that allows for both proximity-mode fuzing as well as orbital reconnaissance of the NEO? In a conventional system, there is not room for both systems. But we are not bound by such constraints; the design space should be opened up to allow for both.
3. **Make as much of the device unclassified as possible.** There are likely some areas of development which will never be unclassified. But we should strongly consider design choices that do not require classification. If we do this, then we can welcome international arms inspectors without worry.
4. **Offer a kill switch to peer nuclear states.** As a show of good faith to the international community – especially those nations with whom the United States has frosty relations – we could install a kill switch on board the space vehicle that would dud the device in the event of a “kill” command from a peer nation. This would further cement international support for such a mission. The design of such a system, the distribution and custody of authorized codes to recipient nations, and the command-and-control of such a system would need to be seriously studied. I foresee it as the most contentious research direction of the four I have outlined, and a successful mission that enjoyed broad international support would not require it. But the idea does bear further consideration.

The above suggestions do not need to be accepted as all-or-nothing. Any one of them could mollify tensions around such a device while simultaneously improving the freedom of designers.

2. METHODS

The R&D program outlined above could grow quite broad in scope, and it would certainly exceed the current funding allocated to this project. But, as a demonstration of some of the improved radar performance that could be capitalized upon, I have explored one question: how would a radically different space vehicle geometry impact the time required to ring down?

Ringdown is the name given to a class of problems which study how long it takes electromagnetic (EM) energy to leave the simulation volume. “Successful” ringdown depends on the system in question as well as its desired mode of operation. Broadly speaking, a simulation of ringdown asks: if we emit a signal from the transmitter (Tx), how long do we have to wait until the power at the receiver (Rx) is low enough to open the receive gate and *not* damage any internal circuitry?

Transmitted signals tend to be very high-power in order to make up for assumed losses and the R^{-4} dependency of signal attenuation embodied in the radar range equation. This ensures that enough signal reaches the Rx to achieve a required signal-to-noise (SNR) ratio. However, once the Tx radiates, it also excites the RV and turns the whole structure into an antenna for a time. There is generally some attenuation that one can take credit for due to the physical separation between Rx and Tx, but in practice, the received signal immediately after transmission is still too large. It might damage internal electronics, and therefore the Rx gate is shut until the initial radiation lingering from the Tx has died down and the reflected EM from the target is expected. If proximity-mode fuzing is required, then radar designers need to push this ringdown time to be as low as possible.

I have kept the “requirements” for this ringdown study as broad as possible, both because there are no specific requirements for the space vehicle as yet, and also to avoid unintentional association with any existing program. The purpose of this study is to illustrate the physics of ringdown, rather than to make definitive statements about any given system. As such, signals, requirements, and geometries will be kept as general as possible.

In this simulation, I generate a Gaussian sine wave in the S-band (2-4 GHz) with a center frequency at 3 GHz. This Tx signal excites an electrically short monopole antenna. An identical Rx antenna exists on the opposite side of the space vehicle. The exterior is modeled as perfect electrical conductor (PEC), and there is a 10 mm layer of radar-absorbing material (RAM) within, boasting a dielectric loss tangent of $\tan \delta_e = 10^{-2}$. We consider two general shapes for the space vehicle: a sphere and a cone. These respectively represent a terrible choice and a practical choice for a RV in atmospheric conditions. Both shapes have ports that allow EM energy to enter and exit the interior. This represents a situation that commonly obtains in practice, where cavities within the RV serve as reservoirs for EM energy.

In the figures below, Figure 1 shows the conventional conical geometry. The cone has a bottom radius of 300 mm and a height of 1200 mm. Figure 2 shows a hypothetical spherical space vehicle design, where the sphere has radius 300 mm. The geometry of both shapes is chosen so that the internal volumes are approximately equal, and therefore, similar total EM energy might exist within both as a resonance. Figure 3 shows a detail of how the electrically short monopole antenna (10 mm long, as compared to the center wavelength of 100 mm) is excited by the 50 Ω port.

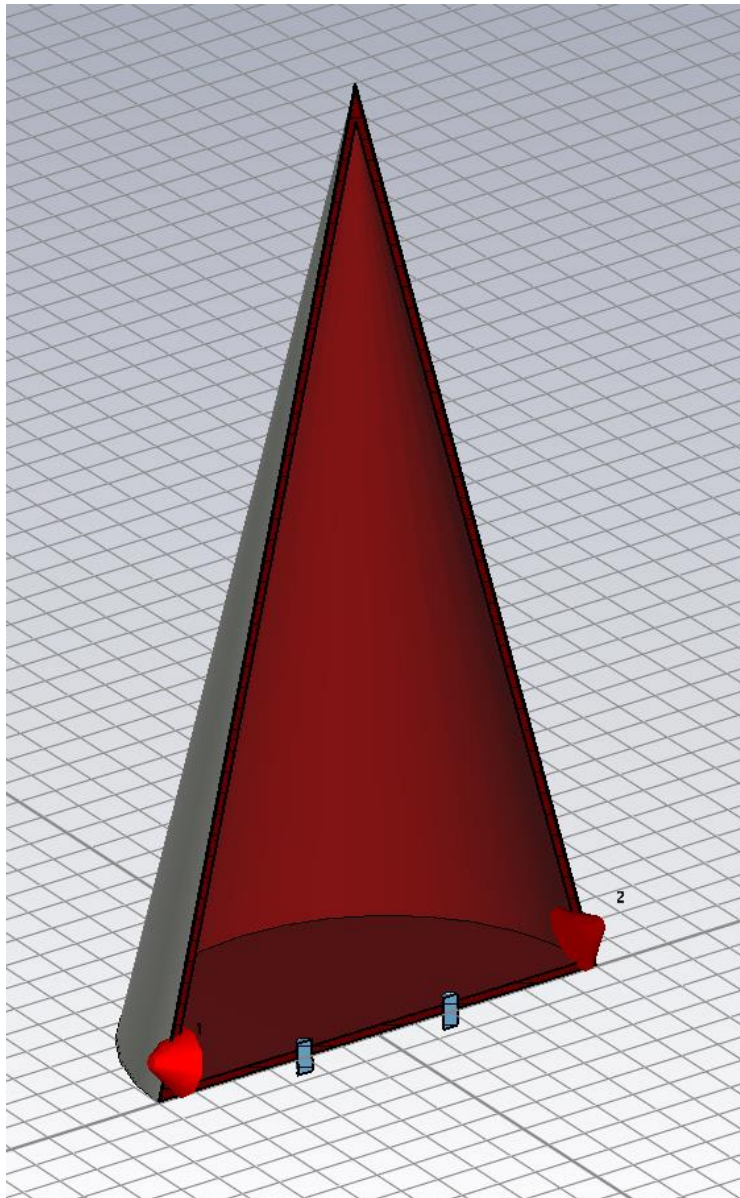


Figure 1: The conventional, conical RV geometry. Note built-in “leaks” (blue), radar absorbing material (red), and ports (red arrows).

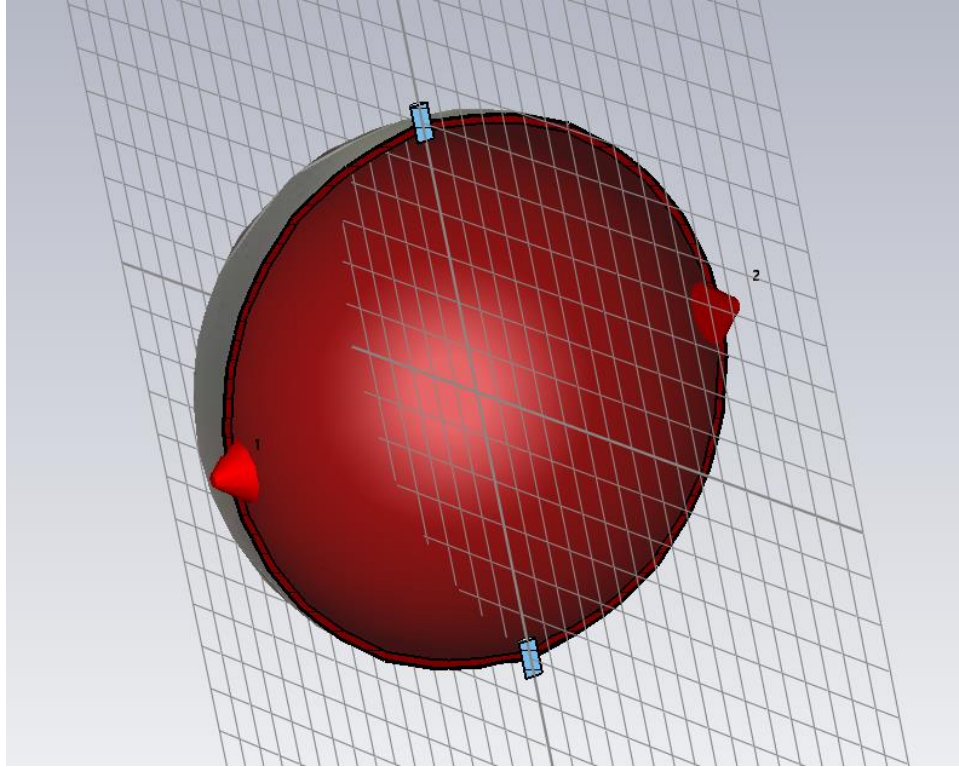


Figure 2: the hypothetical spherical geometry. There are still ports on both sides, as well as leak locations.

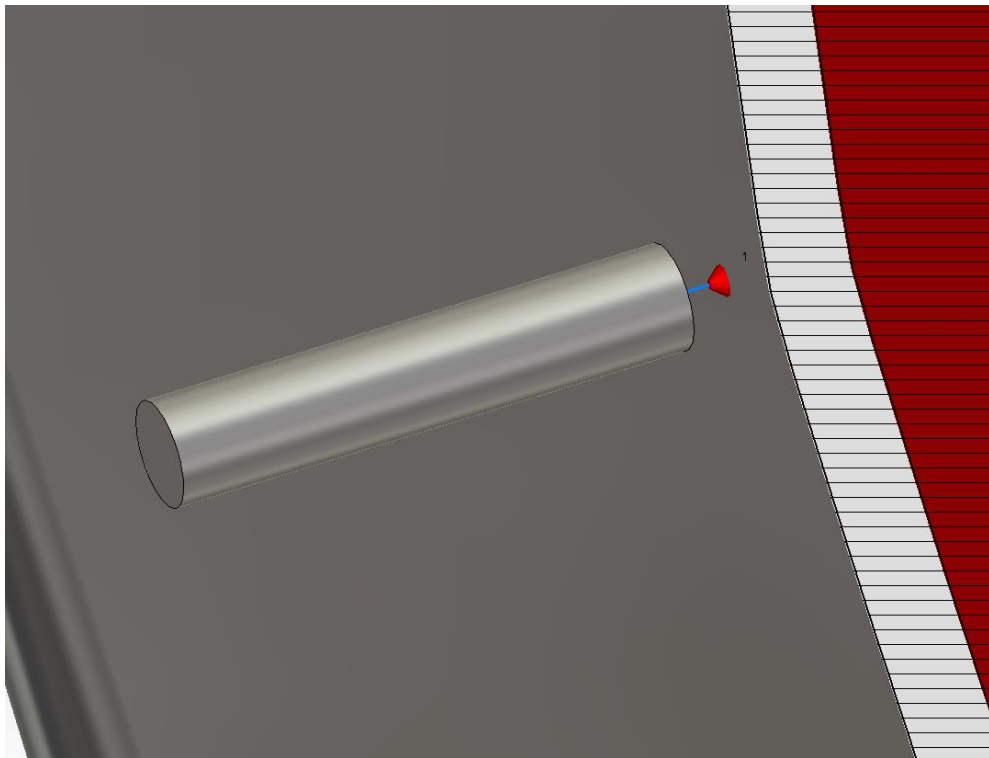


Figure 3: a detail of the voltage excitation (blue w/red arrow) and the electrically small monopole antenna which it excites.

In both cases, I excite Port 1 with a Gaussian sinusoid and leave Port 2 off, while monitoring the voltage excited there. All simulations were performed in CST Microwave Studio.

3. RESULTS

For the purpose of this study, I enforce the “requirement” that the Rx signal should be 150 dB below the peak Tx signal. The ringdown time is then defined as the earliest time at which this occurs *without the Rx signal getting back up to within 150 dB of the Tx signal*. This extra requirement is needed because, owing to the high Q factor of resonant cavities, the combination of radiation on the skin of the RV with internal EM energy re-entering the external region can be complex and difficult to predict. The specific value of 150 dB is completely arbitrary. The Tx/Rx signals for the conical geometry are given in Figure 4:

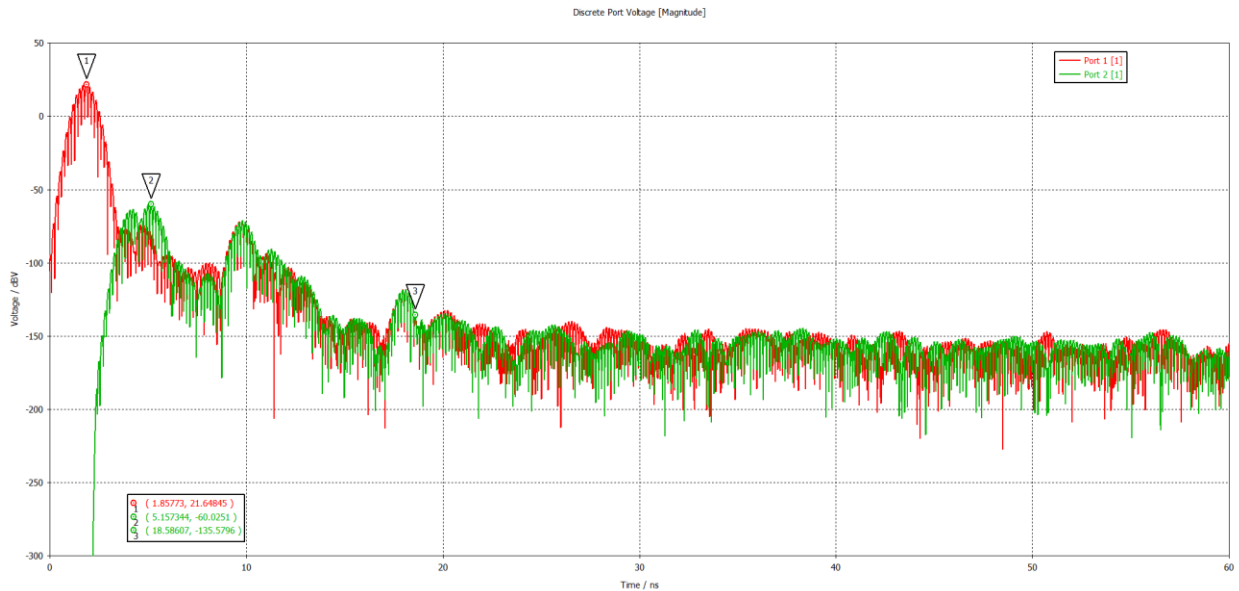


Figure 4: Tx signal (red) and Rx signal (green). There is approximately 81 dB of isolation due to the geometry alone, and 150 dB ringdown occurs at approximately 16.7 ns.

We can see from the above chart that the Rx signal never comes to within 81 dB of the Tx signal. This is known as the relative isolation of the two ports and is due primarily to the placement of the two ports on the body. If they were very closely spaced, this value would be much lower in magnitude, and more time would be required to ring down to a desired attenuation. The equivalent data for the spherical vehicle geometry is given in Figure 5:

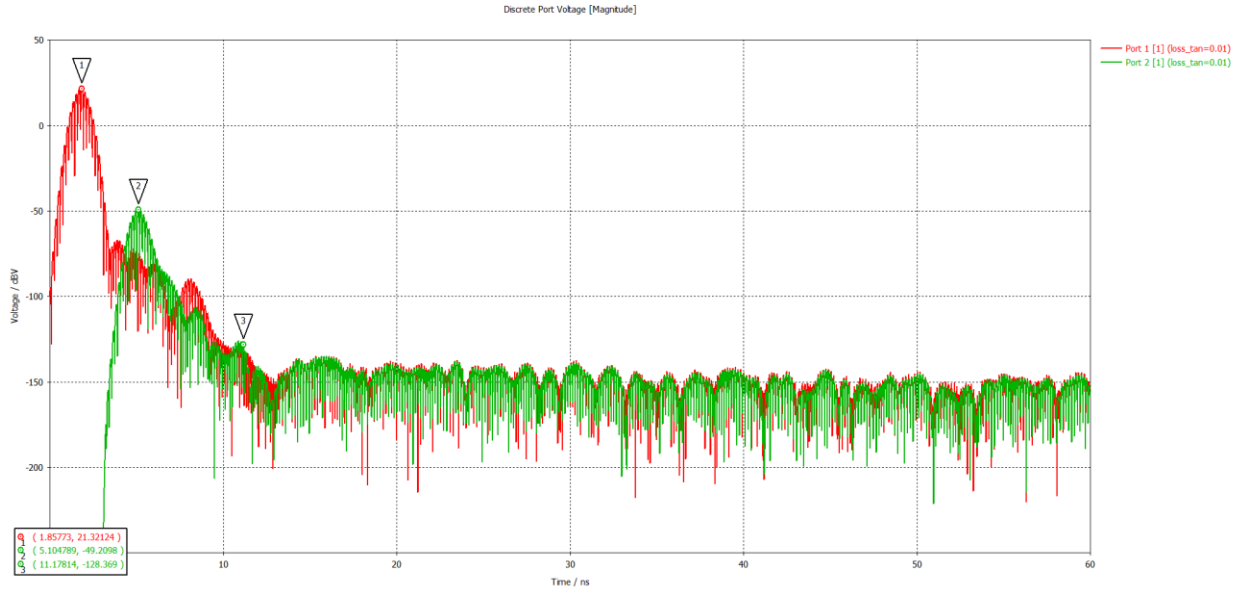


Figure 5: Ringdown data for the spherical vehicle.

Here, the ringdown requirement is satisfied at a much shorter 9.322 ns interval, even though the relative isolation of the two ports is only about 60 dB. This brings us to the question: why do we care so much about ringdown in the first place? If we wish to operate in proximity-fuze mode, then we want to get as close as possible to the target prior to detonation. The shorter the ringdown time, the closer we can get to the surface. Given that the speed of light is approximately one foot per nanosecond, the spherical vehicle can get approximately 3.5 feet closer than its conical counterpart, meaning that energy is delivered even more efficiently into the asteroid. This is especially important if the radius of the asteroid is comparable with the standoff distance; you could be wasting a considerable amount of x-ray energy that radiates out into space and does not ionize the surface of the asteroid. Getting as close as possible ensures the most efficient deflection possible.

This ringdown study is only meant to be an illustration of what performance parameters can be improved if we embrace novel design architectures. There are obvious limitations to the work presented above: the interiors of RVs/SVs are not hollow, and we cannot place RAM on every surface we might wish to. Results with more realistic internal geometry will likely not be as optimistic as those presented here. That said, if the design matures to the point of having a realistic internal geometry, we can exploit the methods of this study to optimize those structures, too.

4. DISCUSSION

In this paper, I have advanced some novel design considerations that could simultaneously improve the performance of a planetary defense mission while allaying concerns that the international community might have about such a mission. The biggest such concern is that a peaceful asteroid deflection mission undertaken by the United States could meet skepticism from the international community and escalate international tensions beyond necessity. If we design a space vehicle whose very nature precludes the possibility of belligerent use, this would build confidence in the mission. A device that would be an operational failure if used in a re-entry environment – which will never occur in a deep-space deflection mission – would be one way to achieve this aim. It is my opinion that diplomatic and policy concerns could, and ought to, advance in tandem with design priorities.

As a demonstration of winning the engineering and diplomatic battles simultaneously, I have offered a sample study of how one performance parameter (to wit, radar ring-down) can be improved if we abandon traditional nuclear device architecture. Reducing the time it takes for the signal at the receive port to attenuate to a given value will allow a space-based nuclear explosive to detonate much closer to the surface of a near-earth object, should that be deemed optimal. This results in a more efficient transfer of momentum to the object, thereby increasing the probability of success of a planetary defense mission.

My objective with this paper is to illustrate that there are very tangible benefits to pursuing a novel design concept. We do not have to sacrifice performance in order to adapt to this new diplomatic and engineering environment; in fact, we may even increase operating margins in areas such as radar ringdown. If we exploit the new opportunities and challenges of the deep space operating environment, we can guarantee the survival of the human race while winning a broad base of support from the international community, and nuclear-armed states in particular.

5. REFERENCES

- [1] United Nations Office for Outer Space Affairs, "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," [Online]. Available: <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html>. [Accessed 24 August 2024].
- [2] D. A. Koplow, "Exoatmospheric Plowshares: Using a Nuclear Explosive Device for Planetary Defense Against an Incoming Asteroid," *UCLA Journal of International Law & Foreign Affairs*, no. 1, pp. 76-158, 2019.