

A Call to (Considered) Action

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Abstract: The purpose of this paper is to call upon the Congress of the United States to initiate, via the National Research Council or other appropriate body, a formal analysis of the circumstances presented by the close encounter between the Earth and asteroid 2004MN4 in April 2029, and the potential for a subsequent collision with Earth in 2036. Informal analysis indicates that the accuracy of our knowledge of the asteroid's trajectory using optical and radar tracking is likely to be inadequate to make a timely deflection decision in the improbable event that one should be needed. Should this claim prove to be correct after formal analysis serious consideration should be given to placing a radio transponder on 2004MN4, perhaps as one of several scientific objectives. This mission should be launched in the near future in order to provide adequately accurate trajectory information about the asteroid by 2014, the approximate date by which a deflection mission decision, if required, would have to be made.

(Author's note¹: While the primary data for all analyses and graphics in this paper are obtained from official governmental sources the conversion of these primary data to graphical form is the responsibility of the author alone. The conversion of the official data to the graphical form herein is done primarily to make this data accessible and understandable to the general

public and policy makers. Since the conversion processes utilized are replete with subtle calculations and approximations the author's first call is to have the fundamental elements of the logic presented herein independently and professionally verified.

Unfortunately at the present time there is no agency of the US Government to which the issue of protection of the public and property from the impact of near-Earth

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asteroids is assigned. The secondary call of the author is therefore to call on the US Congress to initiate a process wherein such assignment of responsibility will be made.)

Introduction

The near-Earth asteroid (NEA) 2004MN4, discovered in 2004 through the efforts of NASA's Spaceguard Surveyⁱ, will make an unusually close pass by the Earth on April 13, 2029ⁱⁱ. This asteroid, estimated by NASA's Jet Propulsion Laboratory (JPL) to be 320 meters in diameter, will come within 30,000 km. of the Earth, passing just behind the Earth in its orbit but well within the geostationary satellite orbit. A collision with the Earth during this 2029 close encounter has been definitively ruled out. Observers in Europe and North Africa, however, will be treated to an unusual sight; the opportunity to view an asteroid with the unaided eye as it passes through the early evening sky toward the just set Sun.

This close encounter with Earth will significantly alter the orbit of the asteroid and create a low, but real possibility that the asteroid will return to impact the Earth seven years later on April 13, 2036ⁱⁱⁱ. The probability of this impact, based on our current best information, is slightly less than 1 in 10,000. (while seemingly a low probability 1 in 10,000 is almost identical to the probability of the average American

driver having an auto accident on any given day^{iv}) Due to the near-center location of the 2036 keyhole in the error ellipse it is anticipated that the probability of impact will gradually increase to about 1 in 3,000 over the period of the next year^v. From mid-2006 through late 2012 the asteroid will be largely out of sight of the Spaceguard telescopes with only two potential opportunities during that time to further refine its orbit.

When 2004MN4 comes back into view in late 2012 it is highly likely that we will learn that it is no longer a threat to Earth. However there is a slim chance that we will not be able to draw this conclusion and that an impact will still be possible.

Due to the unique orbital circumstances posed by this asteroid's close encounter with the Earth in 2029, unusually accurate knowledge of its orbit is required in order to know, in time to take protective action, whether or not it is headed for an impact. Given that a decision to mount a deflection mission would be required by 2014 in order to design, manufacture, launch, and operate such a mission, we are currently confronted with the circumstance that our best optical tracking will be inadequate to enable us to make such a momentous decision. Using optical information alone, it will appear that the maximum probability of impact is approximately 1 in 100, even if the asteroid is in fact headed for a direct impact with Earth. Given

that the corollary to this probability statement is that there will appear to be 99 chances out of 100 that the asteroid will miss us, launching an expensive deflection mission will be problematic at best.

There is a possibility in January 2013 that we will be able to see 2004MN4 using active Earth-based radar^{vi}, albeit this is far from certain. If this attempt is successful the accuracy of our impact prediction will improve to perhaps 1 in 50.

If, however, a scientific mission to the asteroid is performed prior to 2014 our knowledge of its impact probability in 2036 will be materially improved. Any such mission will routinely carry with it a radio transponder which would, by its presence, improve our knowledge of the asteroid's orbit by approximately a factor of 10 over optical measurements^{vii}. In the low probability case that the asteroid is indeed headed for an impact, we will be able, with a transponder on the asteroid, to judge by 2014 whether a deflection mission is necessary. A probability of impact of 1 in 10 should provide a more than adequate basis for preparing a deflection mission.

The question arises as to whether the expense of an immediate science mission to asteroid 2004MN4 is warranted. From an economic point of view the justifiable expense to mitigate the cost of an undesired event is determined by the product

of the probability of the event occurring and the cost of the event were it to occur. In this instance where the impact "path of risk" passes from the western Pacific Ocean north of Japan, along the Mexican west coast, through Central America and out into the Atlantic Ocean, the most likely result of a collision with asteroid 2004MN4 in 2036 is a massive tsunami. The societal cost of a tsunami which would be generated by the impact of this asteroid is estimated to be \$400B^{viii}. Given that the current probability of impact is 1 in 10,000 the justifiable investment in current action to mitigate against this eventuality is \$40M. By mid-2006 the probability of impact (and with it the justifiable investment in mitigation) is likely to increase by a factor of 4 and by mid-2012 by a factor of 10. The cost of a \$3-400M scientific mission to the asteroid would therefore be a rational and prudent investment in public safety.

The analysis presented in this paper is, of necessity, a first order approximation only. It needs to be formally investigated and refined by competent experts.

There is, however, no agency of the US Government whose responsibility it is to address the issue of asteroid impacts with the Earth and the multitude of policy issues raised by NEA impacts and deflection operations. While the general public may assume that NASA has such responsibility this is not the case; NASA has no such

responsibility and is, in fact, a somewhat reluctant agent in the current NEA discovery program.

The purpose of this paper then, based on both the specific situation re asteroid 2004MN4 and the general circumstance of no assigned responsibility for protection of the Earth with respect to asteroid impacts, is to call upon the Congress to act. Congress is called upon to investigate this matter and to direct the National Research Council or other competent body to recommend 1) appropriate action in the specific instance of asteroid 2004MN4 and 2) in the general case an appropriate assignment of governmental responsibility for NEA matters.

The Threat

The basic scenario, albeit highly improbable, which might require a deflection mission for 2004MN4, is entirely driven by the asteroid's close encounter with the Earth on April 13, 2029. (See Figs. 1-3) This close encounter, a priori a highly improbable event in itself^x, will cause a major change in the orbit of the asteroid as it passes by Earth, resulting in the possibility of resonant returns to the vicinity of the Earth in 2034, 2035, 2036, and 2037. The 2036 return is of highest interest since while all four return resonances lie within the current uncertainty ellipse of the asteroid as it passes by in 2029, it lies closest to the centroid^x.

Each of these resonant return possibilities has associated with it a "keyhole", a small region slightly further from the Earth than the resonance line per se, which would, should the asteroid pass through it result in an impact at the time of the resonant return. The width of the 2036 keyhole is approximately 600 meters. The critical question to be answered then, in time to do something about it, is whether or not the asteroid will pass through this narrow keyhole in space in 2029.

Another powerful effect of the 2029 close encounter is that it separates the potential deflection challenge into two very different regions; a deflection prior to the 2029 encounter and a deflection afterwards. The most obvious issue here is that there are only 7 years to act between the 2029 close encounter and the potential impact and therefore waiting until after the encounter to confirm the orbit, and then to plan and execute a mission will be too late. More significant yet is the fact that due to the strong gravitational kick given to 2004MN4 at the time of its close encounter in 2029, a deflection performed after 2029 requires a million times more energy than a deflection accomplished before!^{xi} (Fig. 4) A deflection, if required, should clearly be performed prior to the 2029 encounter, not subsequent to it. In fact a deflection post 2029 is so daunting as to be beyond practical consideration.

If the good news of the encounter dynamics is that a pre-2029 deflection of asteroid 2004MN4 requires very little energy, the associated bad news is that our knowledge of the orbit of the asteroid must be orders of magnitude better than would normally be required in the absence of an encounter. This unusually high precision in our knowledge of the orbit is required to know whether or not the asteroid will pass through the 2036 keyhole (Fig. 3).

The date by which we will have to know whether or not MN4 will be passing through the keyhole (or at least close enough to it to warrant a deflection mission) is determined by the duration of the sequence of events which must precede a deflection operation. This sequence of events would nominally culminate in having successfully deflected the asteroid by no later than 2027 or 2028 in order to provide enough cushion to adjust to surprises encountered during the process. (Given that an asteroid has never been deflected from a pending Earth impact an even earlier date might be prudent) Prior to 2028 the sequence must include, inter alia, the deflection decision, the mission planning and design, manufacturing, assembly and testing of the spacecraft, launch, rendezvous, docking, and the deflection operation itself. It is difficult to imagine compressing this challenging sequence into less than 14 years, thereby leading to a 2014

date for having adequate information to make the deflection decision.

The accuracy of the information required to make a rational deflection decision is not established. No formal consideration of such an operation has ever been made by any responsible agency of the United States government or by any other nation for that matter. Nevertheless one can approximate, using conservative assumptions, what these accuracy requirements might be. It would be argued that were the probability of impact on the order of 1 in 1000 that a billion dollar (+/- 50%) deflection mission would not be considered reasonable, despite the devastating consequences were there to be an impact. The legitimate statement that the likelihood would be 999 out of 1000 that the asteroid would miss the Earth would likely be persuasive. On the other hand, were the probability of impact to be 1 in 2 it is virtually certain that a deflection mission would be ordered. A 50% chance of a 1000 megaton explosion is not a gamble any rational culture would take when it is known that it could be prevented.

The reality we face, however, is that the best we will be able to do by 2014 using optical telescopes to continually refine our understanding of the asteroid's orbit is to predict a statistical probability of 1 in 100 that an impact will

occur, even if the asteroid is headed for a direct impact.

Alternatively, if we were to physically place a radio transponder on the asteroid before 2014 we would be able to predict a collision with a probability of about 1 in 10 by the time we would have to commit to initiating a deflection mission^{xii}.

Whether or not the United States (let alone the world) would be prepared to consider launching an asteroid deflection mission if the best information we can obtain indicates a 10% probability of impact at the time the decision to commit must be made is an indeterminate matter.

Unfortunately there is no institution in the US Government which is assigned to make this decision, let alone address the multiplicity of other policy and operational issues related to NEO impacts.

The Consequences

It is an interesting but little known fact that the specific populations at risk of an asteroid impact are well known far in advance of our knowing whether or not the Earth will be hit. Specifically there is, extending across the Earth, a “path of risk” in the form of a narrow corridor within which, if the asteroid hits the Earth at all, it will impact. This path of risk is well defined at an early date after discovery of a potential impactor since optical

tracking minimizes the uncertainties defining this path quite well.

Using data publicly available at the JPL Sentry site^{xiii} one can deduce the geographic path of risk for all known NEAs with a non-zero chance of impacting the Earth in the next 100 years. Doing this in the instance of the potential 2036 impact of asteroid 2004MN4 one finds a path across the Earth that extends from between the Kamchatka Peninsula and Hokkaido on the west across the Pacific Ocean in an east-southeasterly direction past the tip of the Baja Peninsula, across Central America, and on to the eastern tip of South America. (Fig. 5)

Since approximately 70% of this path of risk lies over water one can estimate the economic cost of this impact occurring over water by utilizing well developed computer models of asteroid generated tsunamis in combination with quantitative models of the economic cost of tsunami events. Based on the impact of an asteroid approximating the characteristics of 2004MN4 and hitting in the Pacific Ocean about 1100 km off the southern California coast (very near the center of the estimated path of risk), the entire western coastline of the United States would experience devastating tsunami waves. (Figs. 6-7) The wave heights from the northern to the southern boundaries of the US will exceed by a factor of about 2 those experienced during the recent

Indian Ocean tsunami^{xiv}. The particular impact point along the path of risk that one uses for economic analysis is, of course arbitrary. However the point selected for the simulation lies at the approximate centroid of the path of risk and was selected on that basis. Were the impact point further to the west the impact on Hawaii, Japan and the East Asian coastline would increase and were it selected further east the impact on California and Mexico would be greater.

The model developed by Chesley and Ward^{xv} for estimating the economic cost of a tsunami impact is generalized for the coastal populations and infrastructure development averaged around the world. For this impact the cost would, for infrastructure losses alone (i.e., no cost assigned to loss of life) total \$400 billion. If the above average infrastructure values of the California coastline were taken into account the loss would undoubtedly be significantly higher.

This number is, of course, only representative since the actual impact point could be either closer to or farther from the US shoreline. There is, however, on a global basis a leveling effect since an impact in the western Pacific, while reducing the losses in the US would raise the losses in Japan and Asia. This economic cost is therefore indicative of what the actual cost would be were asteroid 2004MN4 to impact the Earth.

For the 30% probability of a land impact the estimated cost to society is well established from numerous studies of the losses suffered in nuclear explosions. Unlike the case of an impact generated tsunami where the assumption is made that the primary losses are infrastructure (due to assumed evacuation of the affected population given hours of warning) the primary land impact cost is in lost lives.

It is likely, of course, that the point of impact would be known to great enough accuracy that a massive evacuation would take place prior to impact. Given that the area of destruction from a 2004MN4 impact would approximate that of the state of Connecticut^{xvi} it is difficult to estimate to societal cost of such an unprecedented event. Nor, based on hurricane evacuations, are such calls on the population fully heeded, even with phenomenon with which the public are fully familiar. Given the uncertainty in cost and success of an evacuation it has been ignored in the subsequent assessment and the assumption made that the population is in place at the time of impact.

A comprehensive and authoritative analysis of the cost of asteroid impacts of various sizes is found in the report to NASA by its Near-Earth Object Science Definition Team in August 2003^{xvii}. Based on the cost-benefit analysis performed in this report the mean number of lives lost

in an impact the size of 2004MN4 would be 170,000 people. Based on work by the US Environmental Protection Agency and others, the report utilizes a figure of \$1.7 million as the “value of a statistical life” (VSL). Therefore, based on these figures the approximate societal cost of a land impact by 2004MN4 would be \$289 billion.

The Resolution

If one assumes that committing to a billion dollar deflection mission might require an impact probability of at least 1 in 10 then the size of the error ellipse at the time of decision would have to be on the order of 6-8 km. At the current time the error ellipse is approximately 18,000 km. long (Fig. 2). With an expected reduction in the size of the error ellipse by a factor 4 by mid-2006 and 100 by 2013 using current optical methods (ref. JPL estimates), it is clear that an improvement by an additional factor of 25 will be required for rational decision-making.

Further confounding this already complex situation is the fact that from mid-2006 through late 2012 there will be only 2 brief periods of additional optical tracking information on MN4 due to relative orbital geometry^{xviii}. If in 2013, the 2036 keyhole is still sitting within the reduced error ellipse the best we will be able to say is that the probability of impact is (at most) 1 in 100, even if it is headed directly

for the keyhole and therefore a subsequent impact with Earth. Without better tracking information available it will, at that time, be perfectly legitimate and correct to say that, based on our best knowledge the chances are 99 out of 100 that the asteroid will miss the Earth. It will, at that time, be too late to send a transponder to the asteroid, too late to get better information to resolve this terrible ambiguity in time to deflect the asteroid.

The alternative is to spend ~ \$300M now to send a scientific mission with a radio transponder to MN4. Then, in 2012-2014 we will be able to say (most likely) “the asteroid will definitely miss us” or, (highly unlikely) “it’s got a 1 in 10 probability of hitting us”. Either way our course of action is clear; we either plan another series of cocktail parties to watch the asteroid go by in 2036 (as we will have done in 2029) or we mount the most important space mission in human history.

Is this scenario plausible enough for the nation to now commit \$300M to launch a pre-cursor mission to MN4? On an actuarial basis, and assuming the analysis above is accurate, the answer is clearly yes.

Such a mission however would not need to be justified only by the emplacement of a radio transponder. Other critical instruments would also be carried on the mission and produce vital

information on the surface and interior characteristics of asteroids in general, and on this asteroid in particular. This information is, in itself invaluable, both for scientific knowledge and for the design of systems necessary to perform an asteroid deflection, whenever it becomes necessary. This pre-cursor mission is then quite a competitive

mission even were it not for the unique circumstances presented by this particular asteroid.

Given the tremendous destructive consequences of a predictable and easily preventable impact, obtaining the best possible information on the path of this asteroid now is prudent, to understate the case.

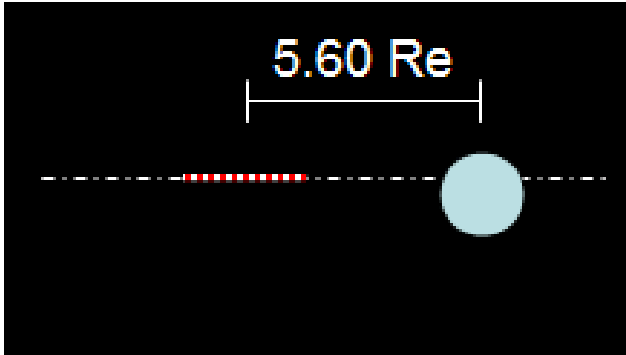


Figure 1.

The error ellipse of asteroid 2004MN4 (dashed red line) and Earth, as viewed from the asteroid nearing its closest approach to the Earth on April 13, 2029. The dotted line represents the orbit plane of the asteroid.

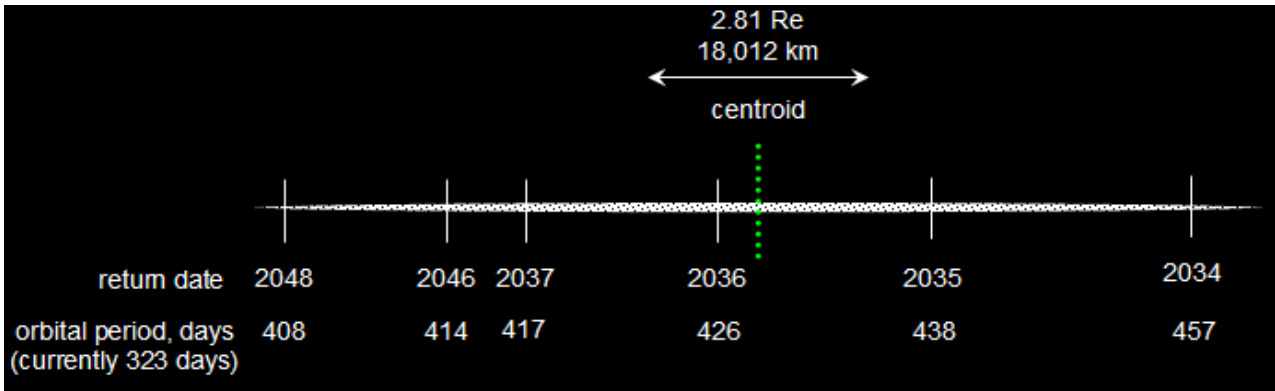


Figure 2. Close-up of the 2004MN4 2029 error ellipse as of 4/14/05. Indicated by the vertical tick marks are the possible resonant return dates and associated orbital periods should the asteroid actually pass at that point.

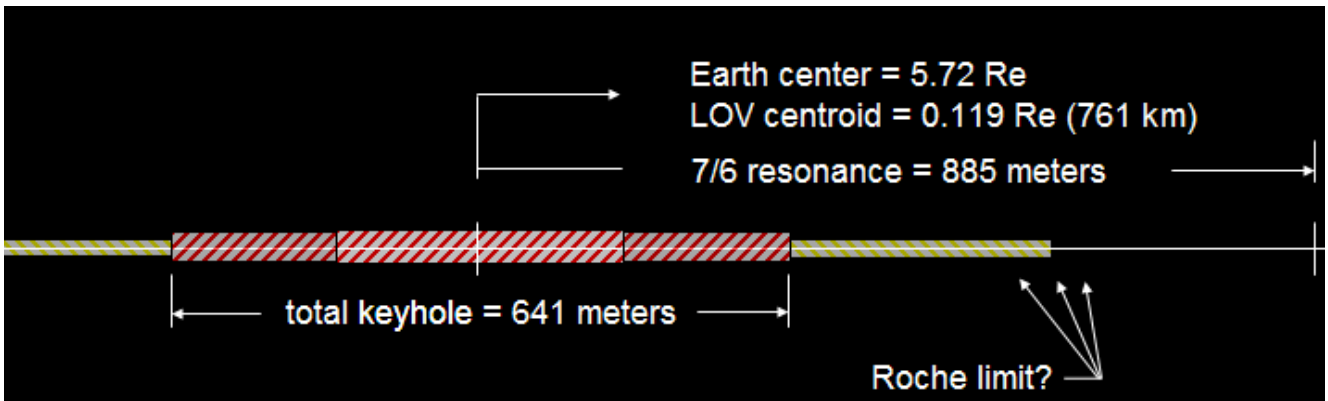


Figure 3. Detail of the keyhole for the 2036 resonance return. The center portion of keyhole does not account for gravitational focusing; total keyhole takes gravitational focusing into account. The extent of the Roche limit for this asteroid is unknown.

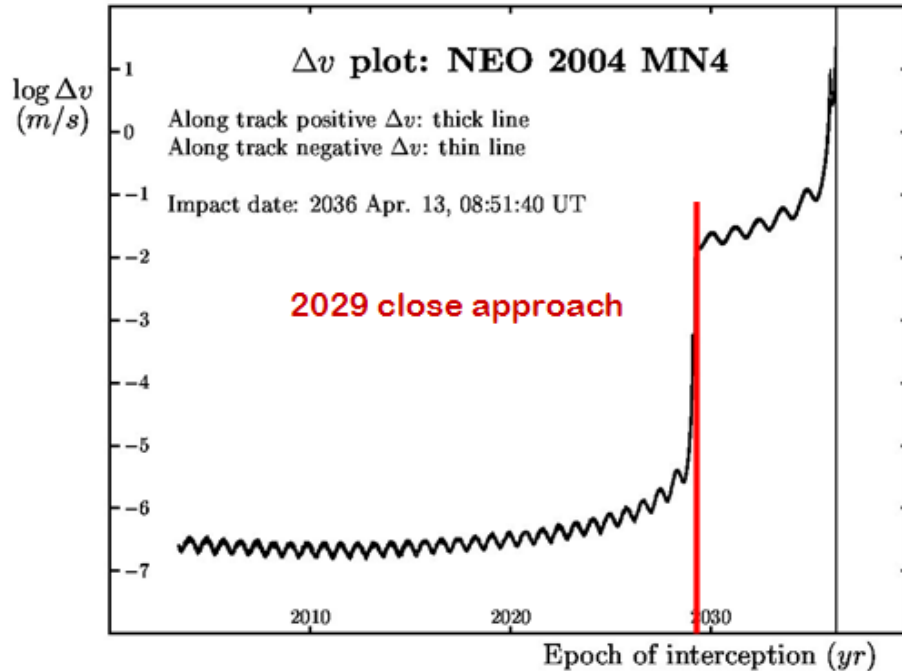


Figure 4. The change in velocity (Δv) required to deflect asteroid 2004MN4 from a 2036 Earth impact vs. date of deflection. (Preliminary data courtesy of Andrea Carusi, Istituto di Astrofisica Spaziale e Fisica Cosmica, Italy and President, Spaceguard Foundation)

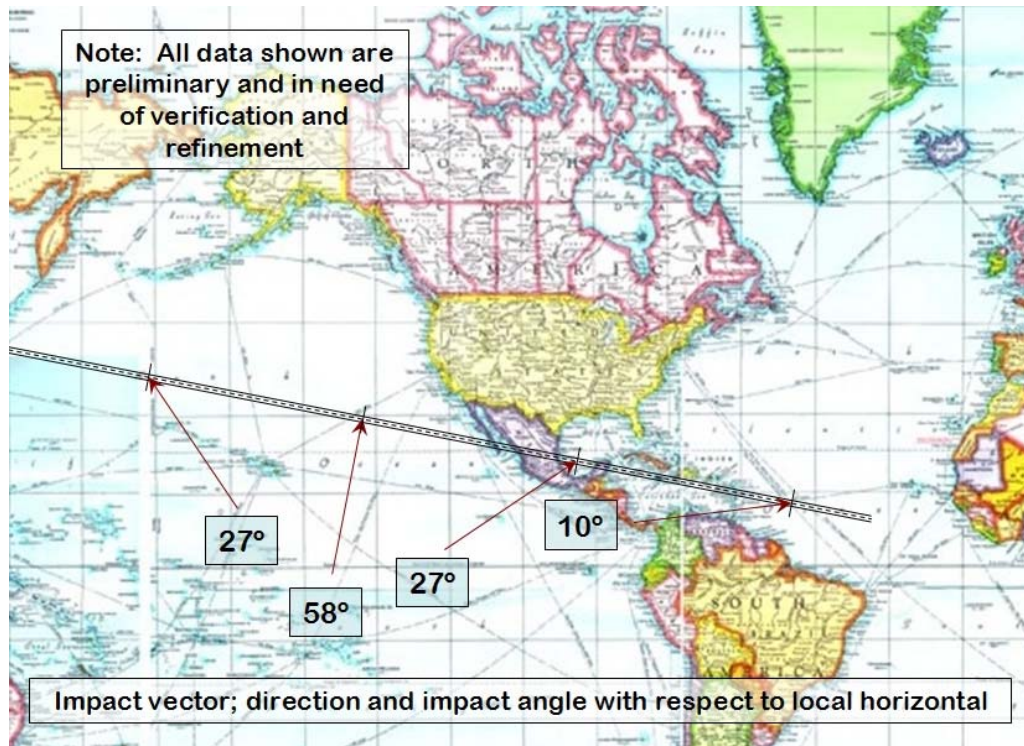


Figure 5. Map showing the approximate path of risk if asteroid 2004MN4 were to impact Earth in April 2036 (Author's note: Corrected 5/25/2005)

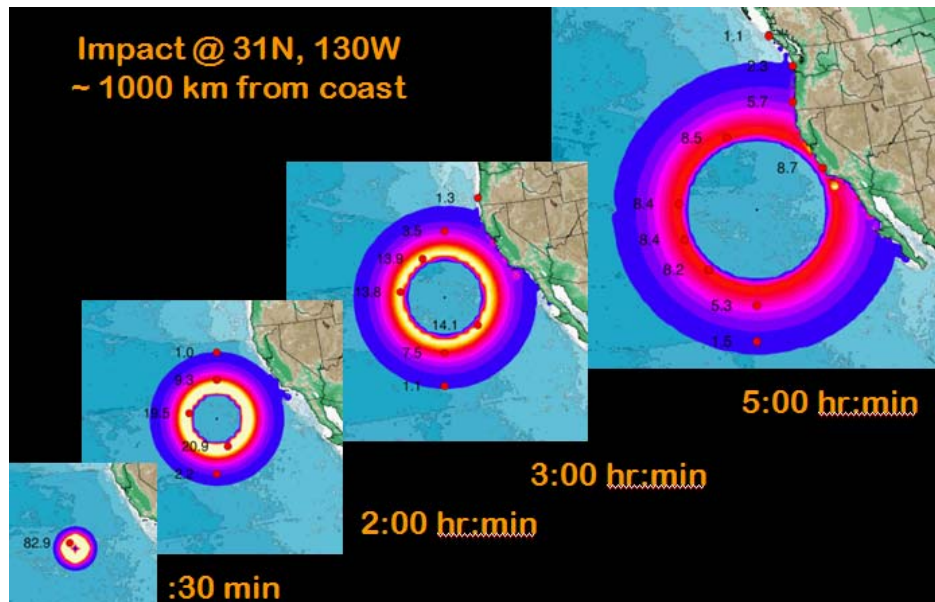


Figure 6. Snapshot sequence of a simulated 2004MN4 tsunami impact approximately 1000 kilometers off the California coast. Numbers represent instantaneous wave heights in meters.



Figure 7. Peak run-up wave heights on the North American Pacific coastline based on a simulated ocean impact of asteroid 2004MN4. Simulation results courtesy of Dr. Steven Ward, Institute of Geophysics and Planetary Physics, University of California, Santa Cruz, CA.

ⁱ Spaceguard Survey is the popular name for NASA's near-Earth object program. See NASA Release 98-123, *NASA Establishes Near-Earth Object Program Office at Jet Propulsion Laboratory*.

ⁱⁱ Radar Observations Refine the Future Motion of Asteroid 2004 MN4, Paul Chodas, Steve Chesley, Jon Giorgini and Don Yeomans, February 3, 2005 (<http://neo.jpl.nasa.gov/news/news149.html>)

ⁱⁱⁱ See <http://neo.jpl.nasa.gov/risk/2004mn4.html> and others.

^{iv} Data from National Highway Traffic Safety Administration (NHTSA). See for example, <http://www.nhtsa.com/people/Crash/crashstatistics/National%20Highway%20Safety%20Data%20charts.pdf>. See also Insurance Information Institute, Facts and Statistics, Highway Safety, http://www.iii.org/media/facts/statsbyissue/highway/?table_sort_735921=4

^v Via informal communication with Don Yeomans and Steve Chesley (JPL), March 29, 2005. Rough estimates of the shrinkage factors of the 2004MN4 error ellipse using optical tracking are 1.1 by mid-2005, 4 by mid-2006, 10 by mid-2012, and 100 by mid-2013.

^{vi} Ibid

^{vii} Via informal communications with Dr. Dennis Byrnes, JPL, April 2005

^{viii} Via personal communication with Dr. Steven Ward, May 2005. See also *A Quantitative Assessment of the Human and Economic Hazard from Impact-generated Tsunami*, 4/7/04, [http://es.ucsc.edu/~ward/papers/tsunami_\(v43\).pdf](http://es.ucsc.edu/~ward/papers/tsunami_(v43).pdf)

^{ix} "On average, one would expect a similarly close Earth approach by an asteroid of this size only every 1300 years or so.", Radar Observations Refine the Future Motion of Asteroid 2004 MN4, Paul Chodas, Steve Chesley, Jon Giorgini and Don Yeomans, February 3, 2005 (<http://neo.jpl.nasa.gov/news/news149.html>)

^x As of May 14, 2005, the 2036 keyhole is located at 0.25338 sigma within the error ellipse for asteroid 2004MN4. See 2004MN4 Earth Impact Table, Sigma LOV at <http://neo.jpl.nasa.gov/risk/2004mn4.html>

^{xi} Figure 4. Preliminary analysis of delta V (change in velocity) required for deflection of asteroid 2004MN4 vs. date, courtesy of Dr. Andrea Carusi, President, Spaceguard Foundation, Istituto de Astrofisica Spaziale, IASF, Rome, Italy

^{xii} The likely major axis of the 2004MN4 error ellipse in 2029, based on the presence of a radio transponder on the asteroid by 2014, would be on the order of 5 to 10 km. Personal communication with Dr. Dennis Byrnes, Deputy Manager, Navigation & Mission Design Section, JPL, Pasadena, CA.

^{xiii} <http://neo.jpl.nasa.gov/risks>

^{xiv} See [http://es.ucsc.edu/~ward/2004MN4\(a\).mov](http://es.ucsc.edu/~ward/2004MN4(a).mov) for a graphic simulation of a tsunami generated by a 2004MN4-like object impacting in the Pacific Ocean approximately 1000 km off the coast of southern California. This simulated impact lies on the "path of risk" addressed in this paper.

^{xv} *A Quantitative Assessment of the Human and Economic Hazard from Impact-generated Tsunami*, 4/7/04, [http://es.ucsc.edu/~ward/papers/tsunami_\(v43\).pdf](http://es.ucsc.edu/~ward/papers/tsunami_(v43).pdf)

^{xvi} *Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters*, NASA, Report of the Near-Earth Object Science Definition Team, August 22, 2003. See Figure 3-1, pg. 23.

^{xvii} Ibid. See Table 3.2, pg. 24 and pgs. 108 & 110.

^{xviii} Via personal communications with Dr. Steven Chesley (JPL), March 29 & May 16, 2005