# NON-GRAVITATIONAL PERTURBATIONS AND THE IMPORTANCE OF RADAR OBSERVATIONS ON NEO TRAJECTORY DETERMINATION

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Radar is a powerful tool for constraining the orbits of near-Earth objects (NEOs). Radar is especially powerful due to its high fractional precision ($10^{-7}$ to $10^{-8}$). Radar ranging of asteroids typically achieves decameter-level precision at distances of up to tens of millions of kilometers. As a result, radar astrometry is extremely important for accurately constraining the orbits of NEOs.

We have developed a high-precision orbit determination tool that can incorporate both optical and radar observations. This tool relies on the the Mission analysis, Operations, and Navigation Toolkit Environment (MONTE), a powerful system developed by the Jet Propulsion Laboratory (JPL) for a variety of space-related science and aeronautical goals (Evans et al. 2016). MONTE is used for trajectory design and spacecraft tracking of most modern NASA missions.

Our tool can model gravitational effects from any set of masses, as well as arbitrary accelerations, including non-gravitational forces. Our orbital integrations account for general relativistic perturbations, perturbations from the major planets, as well as 24 of the most massive minor planets. During close approaches to the Earth, a detailed model for the Earth's gravitational field is accounted for as well. Our tool was successfully used to support the Arecibo radar observations of asteroid 1566 Icarus and to measure its Yarkovsky drift rate (Greenberg et al., 2017).

## 2017 PDC Asteroid Impact Scenario and the Yarkovsky effect

The 2017 Planetary Defense Conference (PDC) features a hypothetical asteroid impact scenario, which will simulate the potential ramifications that an incoming object could have from a readiness and geopolitical perspective. The object, designated 2017 PDC, will be discovered in March 2017, and will have a potential impact 10 years later in July 2027.

Using the simulated trajectory for 2017 PDC as supplied by JPL, we integrated the orbit forward assuming a gravity-only orbit, and an orbit modified by the Yarkovsky effect. We assumed a Yarkovsky drift rate of <da/dt> = 50 x $10^{-4}$ au/My. We then calculated the point of impact for both the nominal and affected orbits. Over the ten years between the last set of observations in 2017 and the impact in 2027, the Yarkovsky effect perturbed the orbit enough to shift the impact location by ~160 km (Fig. 1).

On a global scale, 160 km is not very much. However, depending on the location, 160 km can easily decide in which country the impact will occur.

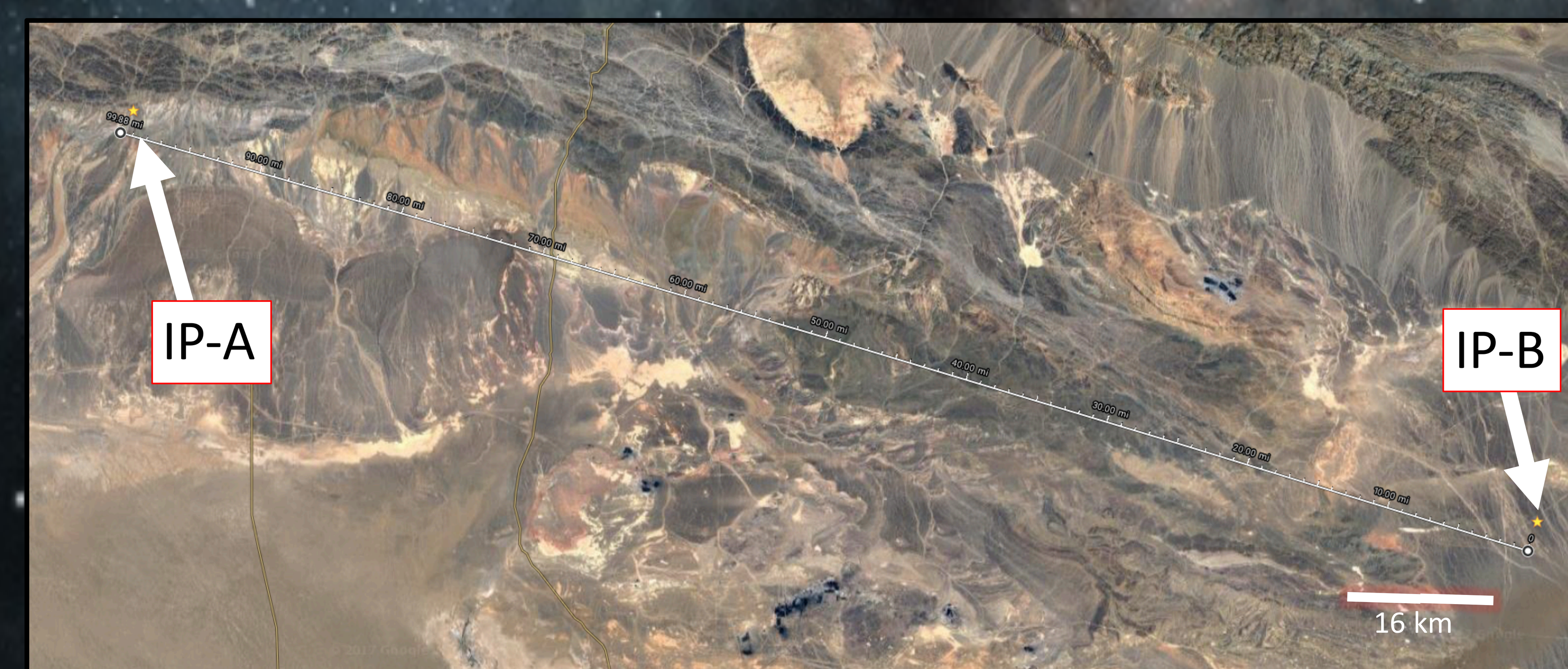


*Fig. 1: A comparison of Earth impact points for an integration accounting for Yarkovsky perturbations (IP-B) compared to a purely gravitational orbit (IP-A).*

## Actual close-approach object: 2012 TC4

Another object of interest is 2012 TC4. This ~40m object was observed for one week in 2012, and is expected to have a close approach to the Earth (at fewer than 10 Earth diameters) on Oct. 12, 2017. Our knowledge of the Yarkovsky effect acting on this object is minimal – due to the short observing arc, we cannot place constraints on any non-gravitational perturbations. However, securing such constraints may be possible if high-accuracy observations are obtained during the 2017 close approach.

To illustrate the benefits of radar measurements for trajectory determination, we analyzed 2012 TC4's orbit using our orbit determination tool, and compared how much we know about the upcoming close encounter to what we would have known had we obtained a single radar range and Doppler measurement of the object during its October 2012 close encounter with the Earth.

## Plane-of-sky uncertainty

Our analysis of 2012 TC4's orbit included 311 optical measurements taken between Oct. 4 and Oct 12, 2012. Using our orbit determination tool, we fit an initial state vector $\mathbf{v_0}$, at a time, $t_0$, corresponding to the last measurement for these observations. Along with a nominal solution for $\mathbf{v_0}$, we also determined the formal uncertainties on the elements of $\mathbf{v_0}$.

We then generated a population of "clone" orbits at time $t_0$, and integrated this population forward in time until the date of 2012 TC4's 2017 close encounter with the Earth. By analyzing the resulting distribution of clone orbits, we can estimate orbital and observational uncertainties at the time of the upcoming close encounter (Fig. 2). Due to the initial large uncertainties in $\mathbf{v_0}$ at time $t_0$, and the fact that 2012 TC4 comes so close to the Earth, the spatial extent of the clone population expands rapidly near the time of the close approach. Between the end of July and September 2017, the along-track 1-sigma optical uncertainty grows by almost an order of magnitude.

To demonstrate the power of radar astrometry, we then re-analyzed the orbit by replacing a pair of optical measurements in the middle of the 2012 observing arc with a pair (1 range, 1 Doppler) of simulated radar measurements, taken from Arecibo Observatory. The simulated range measurement was assigned an uncertainty of 60m, while the Doppler measurement was assigned an uncertainty of 1 Hz. 2012 TC4 was radar-detectable and well within Arecibo's observing window at that time. Figure 2-(d) shows the corresponding plane-of-sky uncertainty at the end of September if that pair of radar observations had been taken. The result was an order of magnitude reduction in uncertainties, along both plane-of-sky dimensions.

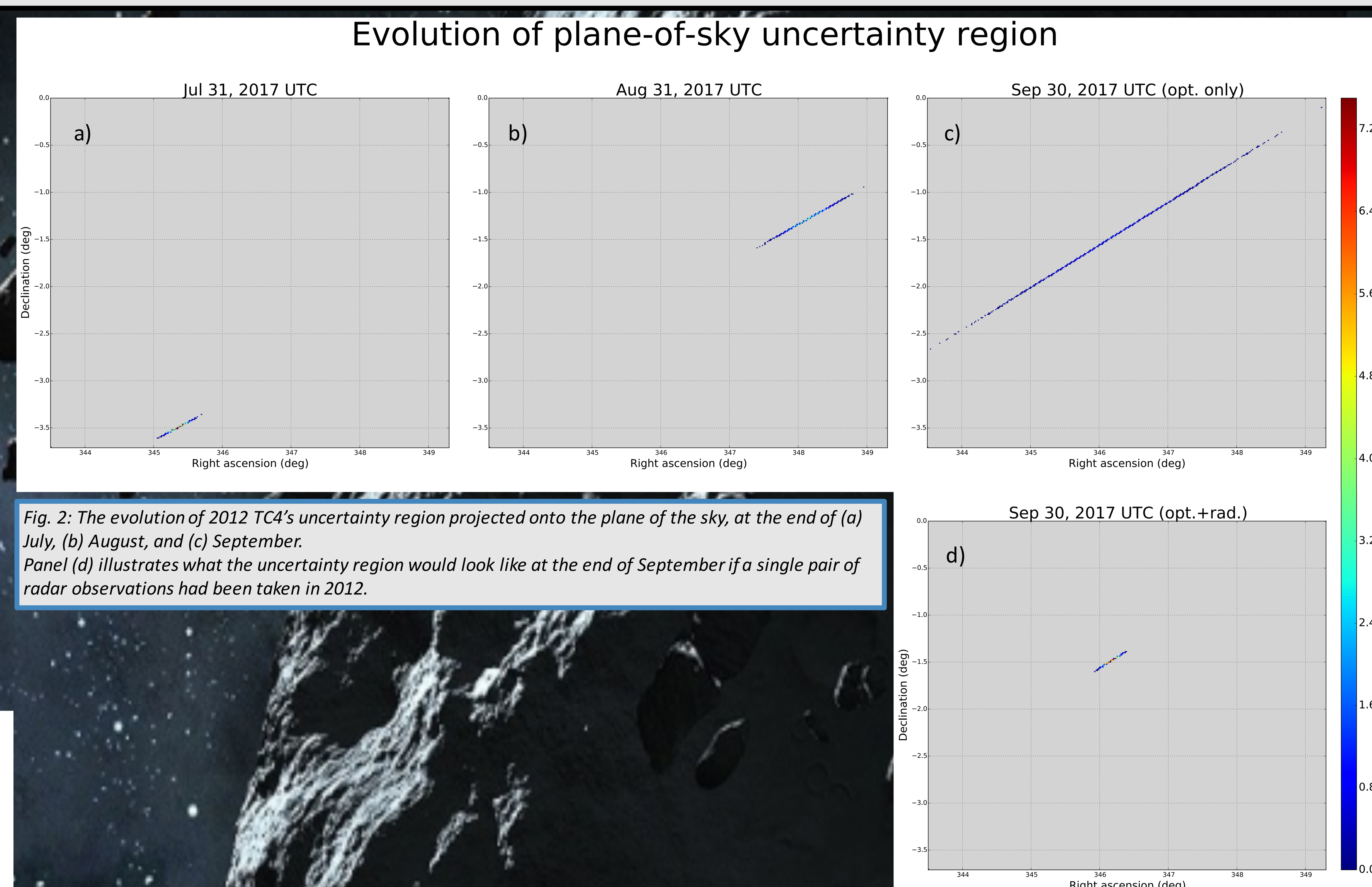


*Fig. 2: The evolution of 2012 TC4's uncertainty region projected onto the plane of the sky, at the end of (a) July, (b) August, and (c) September.*
*Panel (d) illustrates what the uncertainty region would look like at the end of September if a single pair of radar observations had been taken in 2012.*

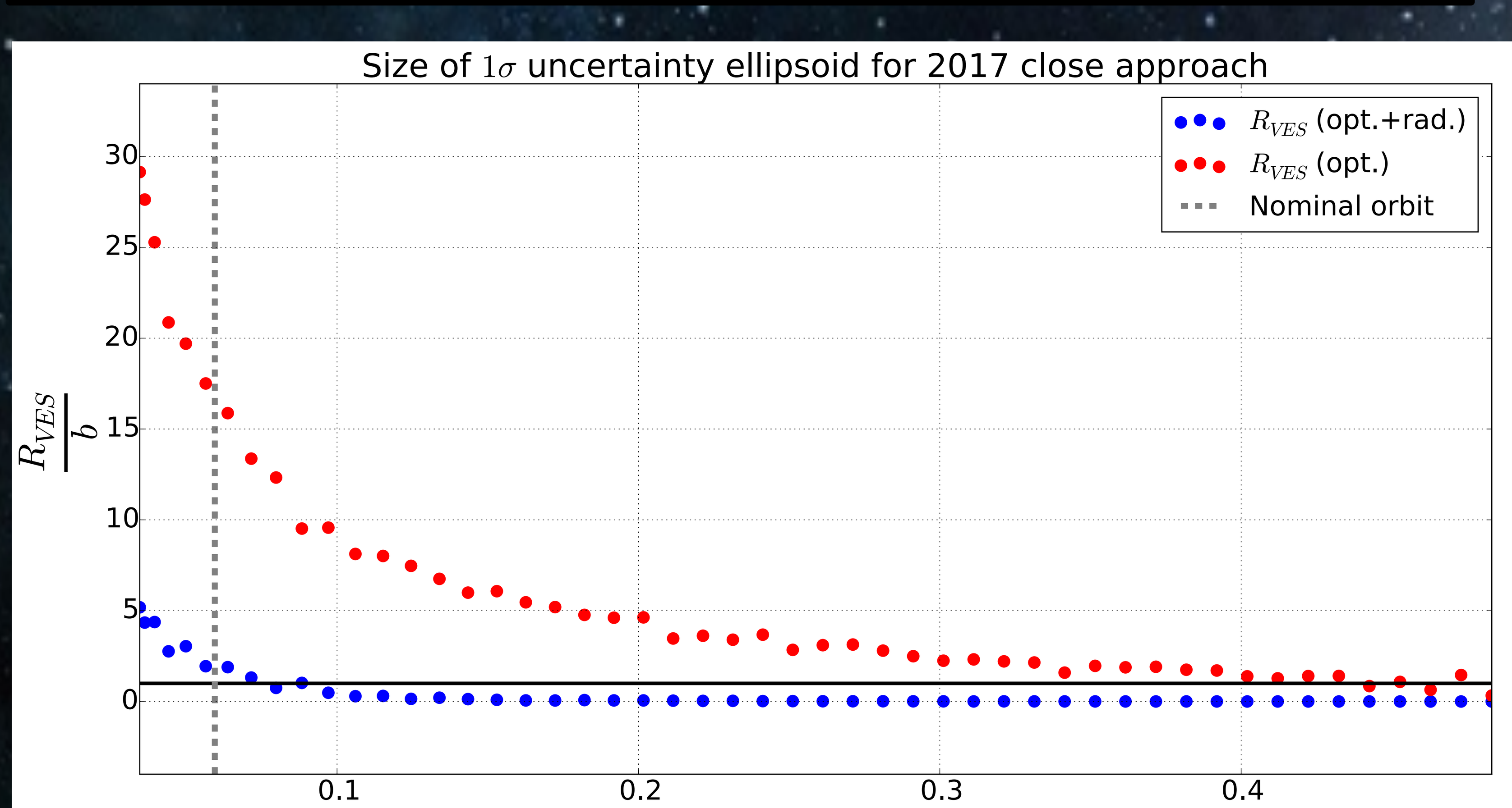


*Fig. 3: The radius of the volume equivalent sphere ($R_{VES}$) for the 1-sigma uncertainty ellipsoid in units of Earth impact parameter b, as a function of b. Points above the solid black line indicate orbits for which the Earth lies inside the uncertainty region's volume equivalent sphere at closest approach.*

## Spatial uncertainty and impact parameter

Radar observations are particularly important for objects that make close approaches (or impacts) with the Earth. We created a range of artificial 2012 TC4 orbits at slightly different close-approach distances (from 0.03 to 0.5 lunar distances (LD) ) on Oct. 12, 2017. We then performed the clone analysis described above to get the spatial 1-sigma uncertainty ellipsoid at the epoch of closest approach for each of these artificial orbits, both with and without a pair of radar measurements.

Figure 3 shows the radius of the volume equivalent sphere ($R_{VES}$) for this uncertainty ellipsoid, in units of the orbit's impact parameter, $b$. With this formulation, points for which $R_{VES}/b > 1$ have the Earth lying inside of the uncertainty ellipsoid's *VES* at closest approach, while $R_{VES}/b < 1$ have the Earth outside of this region. The addition of a single pair of radar measurements reduces the close-approach distance at which we can place the Earth outside of the *VES* by almost an order of magnitude.

Note that $R_{VES}/b$ is not a direct measure of impact probability, because the actual uncertainty ellipsoid is generally highly elongated / non-spherical. However, $R_{VES}$ does serve as a one-dimensional characterization of the volume of the uncertainty region, and thus it is useful to examine the relative change in $R_{VES}/b$ with respect to close approach.

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