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Planetary Bistatic Radar

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Abstract.   Planetary radar observations offer the potential for probing the properties of characteristics of solid bodies throughout the inner solar system and at least as far as the orbit of Saturn. In addition to the direct scientific value, precise orbital determinations can be obtained from planetary radar observations, which are in turn valuable for mission planning or spacecraft navigation and planetary defense. The next-generation Very Large Array would not have to be equipped with a transmitter to be an important asset in the world's planetary radar infrastructure. Bistatic radar, in which one antenna transmits (e.g., Arecibo or Goldstone) and another receives, are used commonly today, with the Green Bank Telescope (GBT) serving as a receiver. The improved sensitivity of the ngVLA relative to the GBT would improve the signal-to-noise ratios on many targets and increase the accessible volume specifically for asteroids. Goldstone-ngVLA bistatic observations would have the potential of rivaling the sensitivity of Arecibo, but with much wider sky access.

1. Introduction

Planetary radar observations have been used to probe the surfaces of all of the planets with solid surfaces and many smaller bodies in the solar system (Ostro 1993, 2003), delivering information on their spins, orbital states, and surface and subsurface electrical properties and textures. Notable findings include characterizing the distribution of water at the south pole of the Moon (Stacy et al. 1997; Campbell et al. 2003), the first indications of water ice in the permanently shadowed regions at the poles of Mercury (Slade et al. 1992; Harmon et al. 1994), polar ice and anomalous surface features on Mars (Muhleman et al. 1991), establishing the icy nature of the Jovian satellites (Ostro & Pettengill 1978), and the initial characterizations of Titan's surface (Muhleman et al.

1990; Campbell et al. 2003). In multiple cases, the ground-based radar observations have served as the foundation for a subsequent space-based mission.

Radar observations are currently conducted in the S band (≈ 2.3 GHz, Arecibo Observatory) and X band (≈ 8.5 GHz, the Deep Space Network's Goldstone Solar System Radar [GSSR]), and future radar observations may also be conducted in the Ka band (~ 30 GHz). All of the planetary radar bands could be within the frequency coverage of the next-generation Very Large Array (ngVLA). As we discuss in more detail below (§3), the ngVLA need not be equipped with a transmitter to provide a powerful enhancement to planetary radar capabilities. Indeed, many of the results summarized previously involved *bistatic* observations in which the radar transmissions originated from one antenna and were received by a separate antenna.

Butler et al. (2004) previously considered the use of the Square Kilometre Array (SKA) as a receiver for a bistatic system. Since the time of their paper, there have been a number of developments, including multiple radar instruments on Mars orbiters, the *Cassini* radar instrument's observations of Titan, and the MESSENGER studies that confirmed earlier radar indications of polar ice at Mercury. This consideration of the ngVLA capabilities is similar to the earlier SKA consideration, but takes many of these subsequent spacecraft-based radar results into account.

We begin by motivating the scientific measurements that could be obtained from various target bodies by bistatic radar (§2), then turn to the specific benefit of the ngVLA in the context of the radar equation (§3), and conclude with a discussion on radar imaging (§4).

2. Target Bodies

In this section, we review target bodies and the science motivations for which future bistatic planetary radar observations could be relevant.

2.1. Venus

Venus is Earth's closest analog in the solar system in terms of its bulk properties, yet Venus and Earth have clearly had different evolutionary paths. There are potentially billions of Venus analogs in the Galaxy, and characterizing and understanding the differences between Venus and Earth has been given additional impetus for understanding the habitability of terrestrial-mass planets. Venus remains enigmatic on a variety of fundamental levels: The size of its core is unknown; whether the core is solid or liquid is uncertain; its atmospheric superrotation, 60× faster than the solid body, is not understood; and the atmosphere exhibits distinctive planetary-scale features that are stationary with respect to the solid body. High-precision measurements of the spin state of Venus with radar have the potential of providing key advances in all of these areas. First, a measurement of the spin precession rate ($\approx 2'' \ \mathrm{yr}^{-1}$) will yield a direct measurement of the polar moment of inertia, which is unknown. The moment of inertia provides an integral constraint on the distribution of mass in a planetary interior. Apart from bulk density, it is arguably the most important quantity needed to determine reliable models of the interior structure of Venus, including the size of its core. Second, a time history of length of day (LOD) variations at the 10 ppm level will identify the geophysical forcings responsible for spin variations, which are primarily related to transfer of angular momentum between the atmosphere and the solid planet. They will provide a crucial input to general circulation models and the key to elucidate poorly

understood phenomena such as superrotation and stationary planetary-scale structures in the atmosphere.

Planetary radar provides a powerful tool for monitoring planetary spin states via observations of the "speckle displacement effect" or *radar speckle tracking* (Margot et al. 2007). Radar echoes from solid bodies exhibit spatial irregularities in the wavefront caused by the constructive and destructive interference of waves scattered by the irregular surface. The corrugations in the wavefront, i.e., speckles, are tied to the rotation of the target body. When the trajectory of the wavefront corrugations is parallel to a roughly east-west antenna baseline, echoes received at two receiving stations display a high degree of correlation. The time of day and value of the time delay at the correlation peak are directly related to the orientation and magnitude of the spin vector of the body. For typical solar system observations, the speckle size ($\sim R\lambda/D$, for a target at range R, observing wavelength λ, and diameter D) is on the order of 1 km and the high-correlation condition lasts for approximately 30 s.

The current approach using Goldstone and the Green Bank Telescope (GBT) yields instantaneous spin rate measurements at the 10 ppm level with X-band transmission from the GSSR and reception at Goldstone and the GBT. For example, with observations obtained between 2002 and 2012, the orientation of Mercury's spin axis has been measured with $5''$ precision, and measurements of the amplitude of longitude librations have revealed Mercury has a molten core (Margot et al. 2007, 2012). The accuracy of these measurements has been validated at the 1% level by independent measurements obtained by the MESSENGER spacecraft during a four-year duration (Margot et al. 2018). On-going observations include Venus, Europa, and Ganymede.

With a single pair of antennas, it is possible to obtain one measurement per day when the stringent geometry and signal-to-noise (S/N) requirements are satisfied. However, measurements accumulate at a slow rate because each measurement requires simultaneous scheduling on two large radio antennas, successful transmission during the appropriate 30-second window, and successful reception at both antennas during the relevant 30-second windows. In order to fully constrain the spin axis orientation, it is imperative to secure observations at a variety of baseline orientations, which typically takes several years. An instrument such as the ngVLA would open up the possibility of securing up to 168 independent measurements in a single 20-minute session with the antennas located in the plains of San Agustin. At conjunction, the individual antenna S/N ratio and the correlation S/N ratio would exceed 100. Although the range of baseline orientations between array elements and Goldstone would remain small at any given observation epoch, the number of independent estimates of the correlation properties would improve the quality of the spin state determination by a factor of $\sqrt{N}$. Because the measurements are instantaneous, LOD variations that occur on 30-minute timescales would be detectable, which would place strong constraints on the mechanisms of angular momentum transfer.

Consequently, the ngVLA would enable (1) improved determination of the spin axis precession and therefore moment of inertia and core size; and (2) improved quantification of the amplitude of LOD variations on daily, seasonal, and secular timescales, providing strong constraints on the dynamics of the atmosphere and its interactions with the solid planet, and exploring a regime that may be common on exoplanets.

2.2.   Asteroids

Radar observations of asteroids provides information on their sizes, shapes, spin states, surface properties, masses, bulk densities, orbits, and the presence of satellites (Figure 1). Recent improvements in transmitter capabilities have resulted in obtaining meter-scale spatial resolutions on various near-Earth asteroids, resolutions comparable to those obtained by spacecraft (either for fly-bys or orbiting). Thus, radar observations complement the fewer, but often more comprehensive spacecraft measurements.
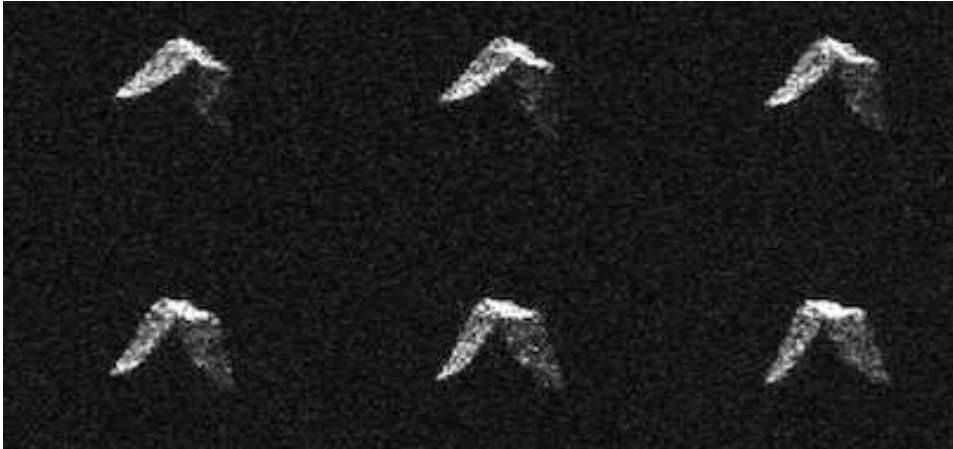

Figure 1.   Radar observations of the near-Earth asteroid 2017 BQ6. Its rotation is apparent, as are the sharp, angular sides. A bright spot particularly apparent in the lower, middle panel may be a few meter-scale boulder on the surface. The sharpness of this asteroid's structure is currently unexplained. The time delay (range) increases from top to bottom, and Doppler frequency increases from left to right. (I.e., the top of the figure is closest to Earth, and the image can be considered to be a "top-down" view.) The color scale shows the echo power strength in units of standard deviation.

There have been a series of comprehensive reviews on radar observations of both near-Earth and Main Belt asteroids (Magri et al. 1999; Ostro et al. 2002; Ostro 2003; Butler et al. 2004; Benner et al. 2015; Naidu et al. 2016). We do not repeat that material here, but focus on specific aspects relative to the ngVLA.

The motivation for radar observations of asteroids is three-fold. First, asteroids represent primitive remnants of the early solar system, and their properties and orbits provide constraints on the formation and evolution of the solar system. Second, they represent targets for spacecraft (e.g., Chesley et al. 2014), for which orbital information and the presence of satellites are essential for mission planning and, for sample return missions, characterization of the surfaces is valuable. Finally, precise knowledge of their orbits is essential to assess the extent to which they might represent impact hazards to the Earth (Committee to Review Near-Earth-Object Surveys 2010), a topic that has increased in visibility over the past decade, and for which a "National Near-Earth Object Preparedness Strategy and Action Plan" has been issued (DAMIEN 2018). In particular, the orbits determined from radar observations are sufficiently precise that they can be used to assess whether a near-Earth asteroid presents any risk of colliding with the Earth over the next several decades to a century (e.g., Ostro & Giorgini 2004).

Specifically for near-Earth asteroids, bistatic radar observations can be valuable in two respects. First, for objects with close approaches to the Earth (short round-trip light

travel times), it can be difficult or impossible to switch a radar facility from transmitting to receiving rapidly enough. Bistatic radar observations either simplify the observations or enable them for objects on extremely close approaches. Second, the increased sensitivity of the ngVLA would increase the range to which near-Earth asteroids could be targeted for radar observations, particularly for targets that are outside of the declination range of the Arecibo Observatory. Particularly from the perspective of planetary defense, obtaining orbits for as many near-Earth asteroids, and especially those classified as "potentially hazardous" is valuable, and the larger the volume that is accessible, the more asteroids that can be targeted. We return to this topic, in quantitative detail, in Section 3.

As quantitative estimates, we consider the improvement in range that the ngVLA might offer over the Green Bank Telescope, which is also used as the receiving element for bistatic radar. (See also Naidu et al. 2016.) If a subset of the ngVLA can be used for bistatic radar reception such that a sensitivity of **three** times that of the current GBT is obtained, it would more than **double** the accessible volume (increase the range by a factor of 30%) for near-Earth asteroid observations; if the sensitivity is **five** times that of the current GBT, it would more than **triple** the accessible volume (increase the range by a factor of 50%). Not only could Goldstone-ngVLA bistatic observations rival those of Arecibo, they would provide access to a much larger fraction of the sky.

Beyond the simple improvement in sensitivity offered by the ngVLA (§3), its antenna distribution offers the promise of improved shape modeling and spin state determinations via radar speckle tracking (Busch et al. 2010). Speckle tracking of asteroids operates in a fundamentally different regime than the case of Mercury or Venus (Margot et al. 2007). The general inability to predict the speckle trajectory in the asteroid case requires an observing configuration in which the speckle size is larger than the antenna baseline, otherwise speckles observed at different stations would not correlate. As a result, the ratio of speckle size to antenna baseline, which determines the fractional precision of the estimates, is three orders of magnitude larger for asteroids than it is for Mercury or Venus. The VLA has a dense set of antennas, but few asteroids approach the Earth sufficiently close that the VLA can be used. For example, for a 100 m object, it must be within about 10% of the lunar distance for the resulting speckle pattern to be comparable in scale to the VLA. Conversely, the VLBA has much longer baselines, allowing use of the technique to larger distances, but it has few antennas, so the number of speckle measurements that could be made is few. With a relatively dense network of antennas and antenna separations to of order 100 km, the ngVLA could be used for objects approaching to within one lunar distance (10^{-3} au), for which the number of objects is higher.

Finally, the dynamics of the Sun-Earth-Moon system allow for small asteroids to be captured into meta-stable geocentric orbits. Various predictions are that there should be a population of meter-scale "temporarily-captured orbiters" or "mini-moons," and at least one such mini-moon, 2006 RH120, has been detected (Kwiatkowski 2009; Bolin et al. 2014; Jedicke et al. 2018). The advent of future large scale-surveys, such as the Large Synoptic Survey Telescope (LSST), may result in several more being found. Due to their small size, such observations are extremely challenging, but feasible, as 2006 RH120 has been detected from Goldstone (Brozović et al. 2016). Not only do mini-moons have small radar cross sections, they are relatively close ($\approx$ 3 s round-trip light travel time). As noted above, with such short light travel times, bistatic observa-

tions would be required to avoid subjecting the transmitter to frequent power fluctuations.

2.3. Icy Satellites/Ocean Worlds

Ground-based radar observations provided some of the first clear evidence for the icy surfaces of the Galilean satellites and subsequent characterization (e.g., Campbell et al. 1977; Ostro & Pettengill 1978; Ostro et al. 1992; Black et al. 2001), demonstrating the capability to probe several meters into the surface. There have been radar observations of Saturnian satellites as well, though these are even more challenging due to Saturn's greater distance (Muhleman et al. 1990; Campbell et al. 2003; Black et al. 2007). Subsequent spacecraft investigations have provided clear evidence that at least some of the moons of Jupiter (Europa, Ganymede, Callisto) and Saturn (Enceladus, Titan), and potentially moons of Uranus (Ariel) harbor sub-surface oceans (Nimmo & Pappalardo 2016). As a consequence, the planned Europa Clipper mission would carry a radar designed to probe and constrain the thickness of the icy shell of Europa.

However, spacecraft missions are infrequent, plausibly only two missions might fly to the outer solar system in a decade, and a radar instrument might not be part of the spacecraft's payload. By contrast, ground-based radar can potentially happen essentially annually, near an outer planet's opposition, when the distance to the icy satellite is minimized.

The orbits of the Galilean satellites of Jupiter are affected by tidal interactions with Jupiter, due to their relatively small semi-major axes. Of particular interest are the tidal responses of Io and Europa as the tidal response of Io is related to the heat dissipation responsible for its active volcanism and the tidal response of Europa is related to the depth of its sub-surface ocean Tidal dissipation is parameterized by k_2/Q, where k_2 is the Love number, which is a measure of the amplitude of tidal response in the body, and Q is the quality factor or a measure of the viscous damping in the body. Both quantities are related to the properties of Jupiter's or satellites' interiors, and the ratio k_2/Q quantifies how the bulge raised by the satellite, or on the satellite, leads or trails its "precursor." The Juno mission will provide estimates of k_2, which can be combined with the radar ranging, to estimate the ratio k_2/Q. Moreover, radar ranging measurements have the advantage of being able to be carried out indefinitely, while the Juno mission is of a limited duration. (At the time of writing, the Juno prime science mission terminates in 2021 June.)

Lainey et al. (2009) used astrometric data to suggest that orbits of Io, Europa, and Ganymede have shifted due to tidal acceleration by 55 km, −125 km, and −365 km, respectively, over a period of 116 years. The highest precision astrometric measurements have a resolution of 75 km and originate from mutual occultations and eclipses.

The Arecibo planetary radar can measure a line-of-sight distance (or range) to Io with 10 km precision and distances to Europa, Ganymede, and Callisto with 1.5 km precision. However, Jupiter is only observable from Arecibo six out of every 12 years because of the constraints of the Arecibo's antenna pointing (declination range −1° to +38°). In 2015, GSSR-GBT bistatic radar demonstrated the capability to obtain ranging measurements of the Galilean moons. Both antennas are fully steerable and allow observations on a yearly basis. A range to Europa was measured with 75 km precision (Figure 2), comparable to the highest precision optical astrometry. However, ranging to Io was not possible with in this bistatic configuration due to low echo strength.
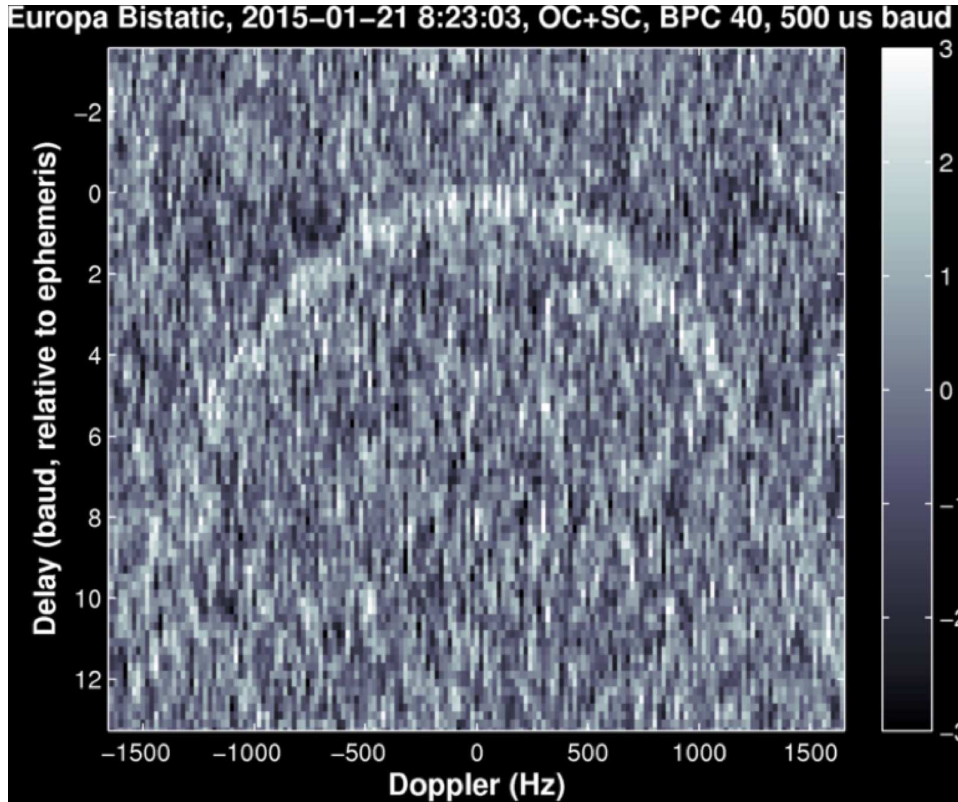
Figure 2.   Goldstone Solar System Radar-Green Bank Telescope delay-Doppler image of Europa. The time delay (range) increases from top to bottom, and Doppler frequency increases from left to right. (I.e., the top of the figure is closest to Earth, and the image can be considered to be a "top-down" view.) The range resolution is 500 μs or 75 km. The color scale shows the echo power strength in units of standard deviation. The scale has been saturated at 3 units in order to enhance the echo outline. With its higher sensitivity, the ngVLA would offer higher signal-to-noise ratios and higher ranging precision.

If ngVLA achieves 3 times the sensitivity of the GBT, it would likely be able to achieve yearly ranging measurements of Europa with sub-10 km precision. Furthermore, it would possible to measure a distance to Io with 100 km precision. If a five-fold sensitivity of the ngVLA materializes, ranging precisions of 15 km–30 km for Io could be obtained. These measurements will contribute to the maintenance of highly accurate ephemerides of the Galilean satellites that would lead to continued improvements in the constraints on tidal dissipation (k_2/Q) and that could enhance, and potentially enable, future missions to these bodies (e.g., monitor Io's volcanism, explore Europa's ice shell for biosignatures).

2.4.   Comets and Interstellar Objects

Much like the case for asteroids, radar observations of comets can provide information on the size, shape, and spin state of comet nuclei.

For instance, the Arecibo radar observed comet 103P/Hartley 2 shortly before NASA's EPOXI spacecraft encountered it in 2010 November. The radar observations determined that the comet nucleus has a bi-lobed shape, a result confirmed by the spacecraft (Harmon et al. 2011). Also, much like the case for asteroids, the radar observations of cometary nuclei complement the fewer, but more incisive spacecraft measurements—approximately five times as many comets have been detected by radar observations as have been visited by spacecraft.

The recent recognition of the first interstellar object, 1I/2017 U1 'Oumuamua, suggested that such objects might have extremely low optical albedos and at least this first object appeared to have a large aspect ratio, potentially in excess of 5:1 (Meech et al. 2017). The number of identified interstellar objects may increase in the future as additional wide-field surveys occur, particularly if the survey strategies explicitly account for the potential trajectories of interstellar objects. Notably, Jewitt et al. (2017) predict that there may be as many as 10^4 such objects within the orbit of Neptune at any given time. If an interstellar object did have a trajectory that took it sufficiently close to Earth to warrant radar observations, constraints on its properties would be invaluable.

3.   The ngVLA and the Radar Equation

The increased sensitivity of the ngVLA would expand the set of targets for traditional bistatic delay-Doppler planetary radar. The classic radar equation is that the received power P_R is (e.g., Benner et al. 1999)

$$P_R = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R^4},$$ (1)

where P_T is the power of the transmitter; the gains of the transmitting and receiving antennas are G_T and G_R, respectively; λ is the operational wavelength; σ is a measure of the radar cross section of the target body; and the range (distance) to the target is R. More concisely, the signal-to-noise ratio of radar observations scales as R^{-4}. This R^{-4} dependence can be understood as the product of two inverse square laws. The transmissions from the transmitting antenna to the target body suffer a R^{-2} loss by the inverse square law. By Huygen's principle, the target body re-radiates, and these emissions suffer an additional R^{-2} loss by the inverse square law.

With a fixed radar transmitter power (and antenna gain), the signal-to-noise ratio can only be improved by using increasing the gain (i.e., sensitivity) of the (bistatic) receiving element. For the ngVLA to participate in this kind of radar observation, it would have to have a "phased array" mode, in which voltages from the individual antennas are summed, after applying the appropriate time delays, so that the array appears as an effective single aperture. A phased array mode would also be valuable for observations of pulsars and for very long baseline interferometry (VLBI) imaging.

4.   Radar Imaging

Existing planetary radar observations with the VLA have been used to image the radar return and make plane-of-the-sky astrometry measurements. Such *bistatic radar aperture synthesis* has produced spectacular images that convincingly demonstrated the presence of water ice at the poles of Mercury and Mars. With a factor of **five** better

angular resolution, the ngVLA could produce a correspondingly better linear resolution on the surface of target bodies. Alternately, an improved angular resolution opens the possibility of producing resolved images of smaller objects or higher spatial resolution bistatic radar aperture synthesis on planets.

For example, de Pater et al. (1994) imaged 4179 Toutatis with the VLA in its A configuration. The asteroid was at a distance of 0.063 au, and the VLA's angular resolution corresponded to a linear resolution of approximately 10 km on the asteroid. They found that the asteroid showed clearly distinct residual radar features, suggestive of a bi-lobed structure, but their estimate of the separation of these features was limited by the VLA's beam size. With the improved angular resolution of the ngVLA, features with scales of about 2 km would have been distinguishable.

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