Relative Planetary Radar Sensitivities: Arecibo and Goldstone

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The increase of the Deep Space Network antennas from 64-meter to 70-meter diameter represents the first of several improvements that will be made over the next decade to enhance earth-based radar sensitivity to solar-system targets. The aperture increase at the Goldstone DSS-14 site, coupled with a proposed increase in transmitter power to 1000 kW, will improve the 3.5-cm radar by about one order of magnitude. Similarly, proposed Arecibo Observatory upgrades of a Gregorian feed structure and an increase of transmitter power to 1000 kW will increase the sensitivity of this radar about 20-fold. In addition, a Goldstone-to-Very Large Array bistatic observation with horizon-to-horizon tracking will have 3.5 times more sensitivity than will a Goldstone horizon-to-horizon monostatic observation. All of these improvements, which should be in place within the next decade, will enrich an already fertile field of planetary exploration.

I. Introduction

Between the mid-1980s and the late 1990s, several upgrades are planned to both the Arecibo (12.6-cm-wavelength) and the Goldstone (3.5-cm-wavelength) earth-based planetary radars. These upgrades, which are already under way with expansion of the DSS-14 (Mars) site aperture to 70 meters, have the potential to increase the sensitivity of earth-based radar observation by one order of magnitude within the next decade. Arecibo upgrades begin with a partial ground screen to reduce background noise. This step is scheduled for completion in the early 1990s. The Arecibo Observatory is also proposing a Gregorian feed and increased transmitter capability for the 1990s. The Gregorian feed will yield higher and more uniform gains together with reduced background noise. The proposed transmitter upgrade at Arecibo will be 1000 kW, up from the current 450 kW. Goldstone radar upgrades include the completed antenna aperture increase to 70 meters as well as the proposed X-band (3.5-cm) transmitter upgrade from the current 350 kW to 1000 kW.

The purpose of this article is to compare the relative capabilities of these two planetary radars both for the existing conditions and for the near-future conditions outlined above. We will generally ignore the 70-meter-wavelength capability of Arecibo and the 12.5-cm-wavelength capability of Goldstone, since the radars' sensitivities at these wavelengths are less than 10 percent of those associated with the shorter wavelengths. Also briefly considered will be a special Goldstone-to-Very Large Array (VLA) configuration proven in 1987 observations of Saturn. This is a bistatic configuration in which Goldstone transmits continuously at a 3.5-cm wavelength, and radar echoes are recorded at the VLA in Socorro, New Mexico. This configuration takes advantage of the Voyager project upgrading of the VLA to X-band capability for the Neptune encounter in 1989. However, this configuration is rarely available, since the VLA is a radio astronomy facility in high demand by that user community.

II. Signal-to-Noise Equations

The discussion of sensitivity will begin with a statement of the radar signal-to-noise (SNR) equation – the usual method for defining figures of merit for these types of earth-based radar observations [1]:

$$SNR \sim \frac{PG^2\lambda^2\sigma(NLB)^{0.5}}{R^4(KTB)} \tag{1}$$

where

P = peak transmitter gain

G = antenna gain

λ = radar wavelength

σ = target cross section

N = number of observations

R = earth–target range

K = Boltzmann's constant

T = system noise temperature

B = receiver bandwidth

L = post-detection integration time

To compare Arecibo and Goldstone on the same target, the radar cross section and the Earth–target range are assumed to be equal. Thus, the relative sensitivity of these two radars becomes

$$\frac{SNR'}{SNR} = \left(\frac{P'}{P}\right)\left(\frac{T}{T'}\right)\left(\frac{B}{B'}\right)^{0.5}\left(\frac{G'\lambda'}{G\lambda}\right)^2\left(\frac{N'}{N}\right)^{0.5} \tag{2}$$

To proceed further, it is noted that the various bodies of the solar system rotate. The radar astronomer often uses spectral analysis to increase the signal-to-noise ratio. Thus, the received bandwidth and the number of observations will vary with wavelength. In particular, we chose B to match the target's rotational frequency spreading so that

$$B = \frac{2\Omega D}{\lambda}$$
$$N = \tau\Delta f = \text{constant}\cdot(\tau/\lambda) \tag{3}$$

where

Ω = target rotation rate

D = target diameter

τ = observation time

Δf = frequency resolution needed to resolve a particular area

In Eq. (3), the product (ΩD) is the limb-to-limb velocity difference and $(2\Omega D/\lambda)$ is the Doppler frequency difference across the target. In Eq. (3), it should be noted that the frequency resolution needed to resolve a particular area (Δf) is proportional to λ^{-1}. Thus, observations at a higher frequency can be conducted with larger bandwidths, which require shorter times per spectrum. This, in turn, yields more observations for a fixed period of time.

Another factor which varies with observation wavelength is antenna gain, G, which is given by

$$G = \frac{4\pi\eta A}{\lambda^2} \tag{4}$$

where

η = antenna efficiency

A = antenna area

When these factors are combined by substituting Eqs. (3) and (4) into Eq. (2), the relative sensitivity of the two radars becomes

$$\frac{SNR'}{SNR} = \left(\frac{P'T}{PT'}\right)\left(\frac{G'}{G}\right)^2\left(\frac{\tau'}{\tau}\right)^{0.5}\left(\frac{\lambda'}{\lambda}\right)^{2.5}$$
$$= \left(\frac{P'T}{PT'}\right)\left(\frac{\eta'A'}{\eta A}\right)^2\left(\frac{\tau'}{\tau}\right)^{0.5}\left(\frac{\lambda}{\lambda'}\right)^{1.5} \tag{5}$$

Several quantities in Eq. (5) vary with the declination of the target. In particular, the total time that a target is within the visibility limits of the Arecibo or Goldstone antennas is given by

$$\tau = 2 \cdot LHA$$

where τ = target visibility time. LHA (local hour angle at the tracking limits) is derived from the following equation:

$$\sin(\mathrm{El}) = \cos(\mathrm{Zen}) = \sin(\phi) \cdot \sin(\delta) + [\cos(\phi) \cdot \cos(\delta) \cdot \cos(LHA)] \quad (6)$$

where

El = elevation limit of the antenna

Zen = zenith limit of the antenna

ϕ = radar observatory latitude

δ = target declination

Total tracking times for Arecibo and Goldstone are shown in Fig. 1. The zenith angle limit for Arecibo is 20 degrees, so observations can be made only when the body lies within 20 degrees of a point directly overhead. The Arecibo tracking time for the planets varies from 2 to nearly 3 hours while a planet is at optimal northern declinations. The elevation limit for Goldstone is 15 degrees; this limit is set by the Federal Aviation Administration for radiation safety. The Goldstone tracking time for ecliptic objects varies from 6 to 12 hours. The Deep Space Network also operates another large 70-meter-diameter antenna at Tidbinbilla, Australia, which is located at a southern latitude within one degree of the northern latitude of Goldstone. Thus, a plot of the total tracking time for Tidbinbilla is simply the mirror image of the Goldstone curve in Fig. 1.

A second consideration for tracking time is that radar experiments consist of repeated cycles of transmission toward the observed body followed by reception of the echoes. These cycles are repeated as long as the body is within the tracking limits of the antenna. The time spent observing the echo is thus roughly half of the tracking time. However, when the special Goldstone-to-VLA bistatic configuration is considered, the Goldstone transmitter is assumed to be on for the entire tracking time, and the total echo reception time at the VLA becomes the entire tracking time as well. Thus, when the ratio (τ'/τ) is evaluated in Eq. (5), we used the ratio of tracking times for the monostatic cases and multiplied this ratio by 1.414 for the bistatic case.

Other quantities in the relative sensitivity equation also vary with elevation–zenith angle. In particular, the Arecibo antenna gain and the receiver temperature vary with zenith angle as shown in Fig. 2.[1] The Goldstone antenna efficiency at 3.5 cm is expected to vary with elevation angle as shown in Fig. 3. These changes of the radar parameters with elevation–zenith angle must be accounted for in our computation of relative sensitivities (Eq. [5]). Several obvious approaches are (1) to replace antenna gain and temperature with an average; (2) to compute an average "sensitivity" for various elevation–zenith angles; or (3) to weigh the "sensitivities" for various elevation–zenith angles and then average these values. We used the third approach, as it simulates the procedures used in the data reduction of Arecibo asteroid observations (S. Ostro, personal communication). The equations for this approach are

$$RS = \frac{S_a}{S_g} \quad (7a)$$

where

RS = ratio of sensitivities

S_a = Arecibo sensitivities

S_g = Goldstone sensitivities

and

$$S = \frac{(W_1 S_1 + \ldots + W_n S_n)}{(W_1 + \ldots + W_n)} \quad (7b)$$

where

S = weighted sensitivity for Arecibo or Goldstone

W_i = weight of the ith observation

S_i = sensitivity of the ith observation

Furthermore, to relate the relative sensitivities given in Eqs. (5) and (7), we require

$$S_i = P(G^2/T)(\tau/2)^{0.5}\lambda^{2.5}$$
$$W_i = \frac{(S_i/S_{i\max})}{T_{\max}} \quad (8)$$

[1] D. B. Campbell, "Arecibo Observatory S-Band Radar Program," NASA Planetary Astronomy Management Committee memorandum (personal communication), 1986.

where P, G, T, and λ are defined in Eq. (1) and τ is the total track time given in Fig. 1 and Eq. (6). The weight is simply the ratio of S_i to the best S_i for the radar in question. Thus,

$$W_i = \text{constant} \cdot \left[\frac{(\text{antenna gain})^2}{\text{receiver temperature}} \right] \tag{9}$$

A summary of major system parameters is given in Table 1. For the VLA configuration, we assumed 27 antennas where each 25-meter antenna had an individual efficiency of 60 percent and a noise temperature of 35 K. We also assumed an array efficiency of 80 percent [2].

III. Relative Sensitivities

The equations for the relative sensitivities of earth-based radars were evaluated for various declinations, yielding the results plotted in Figs. 4, 5, and 6. Figure 4 shows the improvement in Goldstone sensitivity at the 3.5-cm wavelength in relation to both the aperture increase from 64 meters to 70 meters and the transmitter power increase from current (late 1980s) levels of 350 kW to the proposed 1000-kW level in the 1990s. Figure 5 shows the enhancement of Arecibo sensitivity at the 12.6-cm wavelength from current (late 1980s) capabilities to the proposed implementation of the Gregorian feed structure and with the transmitter power increase from current levels of 450 kW to 1000 kW in the 1990s. Figure 6 shows sensitivities for the mid-1980s versus those expected in the mid-1990s, when all Arecibo and Goldstone improvements are in place. The plots in Figs. 4, 5, and 6 are all scaled such that the maximum sensitivity in each figure is arbitrarily set to unity.

The improvements in Goldstone sensitivity at the 3.5-cm wavelength for the already completed aperture increase and the proposed transmitter increase to 1000 kW (see Fig. 4) show an order-of-magnitude improvement between the mid-1980s and the mid-1990s. The improvements in Arecibo sensitivity at the 12.6-cm wavelength from the proposed Gregorian feed and the transmitter increase to 1000 kW (sketched in Fig. 5) show an increase of about a factor of 20. After these improvements, the Arecibo sensitivities have a broader peak in declination, indicating improved sensitivities for targets visible at Arecibo at zenith angles beyond ten degrees. A comparison of Goldstone and Arecibo before and after all of these improvements is sketched in Fig. 6. A horizon-to-horizon Goldstone–VLA observation (a rare experiment, since both antennas would simultaneously observe for around half a day) has about 3.5 times more sensitivity than the Goldstone monostatic observation, as shown in Fig. 6.

IV. Summary

The ability to perform radar astronomy experiments with the Arecibo and Goldstone radars will improve by a factor of ten in the next decade. The Arecibo and Goldstone radars are complementary in several ways. Goldstone can observe bodies with southern declinations beyond Arecibo tracking coverage. While bodies are in northern declinations, the Goldstone 3.5-cm and Arecibo 12.6-cm wavelengths provide dual-frequency observations of the same body.

The order-of-magnitude improvement in earth-based radar capability rests upon implementing a Gregorian feed and a 1000-kW S-band transmitter at Arecibo and/or implementing a 1000-kW X-band transmitter at Goldstone (with rare Goldstone-to-VLA experiments). All of these improvements are being pursued, promising a new era of planetary exploration with earth-based radars.

References

[1] S. J. Ostro, "Planetary Radar Astronomy," in *Encyclopedia of Physical Sciences*, vol. 10, New York: Academic Press, pp. 613–614, 1987.

[2] J. S. Ulvestad, G. M. Resch, and W. D. Brundage, "X-Band System Performance of the Very Large Array," *TDA Progress Report 42-92*, vol. October–December 1987, Jet Propulsion Laboratory, Pasadena, California, pp. 123–137, February 15, 1988.

Table 1. Radar parameters: Arecibo and Goldstone

Radar configuration	Arecibo		Goldstone	
	1980s	1990s	1980s	1990s
Transmitter power, kW	450	1000	350	1000
Peak antenna efficiency	0.55	0.60	0.47	0.63
Antenna diameter, meters	200	250	64	70
Peak antenna gain, dB	71.4	73.7	71.9	73.9
Wavelength, cm	12.6	12.6	3.5	3.5
Nominal receiver temperature, K	35	20	20	20

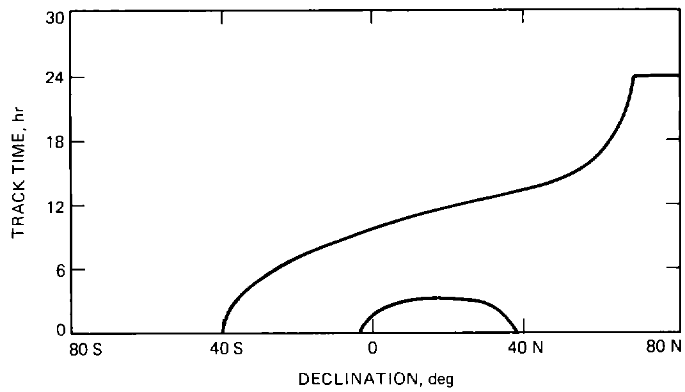

Fig. 1. Total tracking time for the Arecibo and Goldstone radars versus declination, assuming an Arecibo zenith angle limit of 20 degrees and a Goldstone elevation limit of 15 degrees

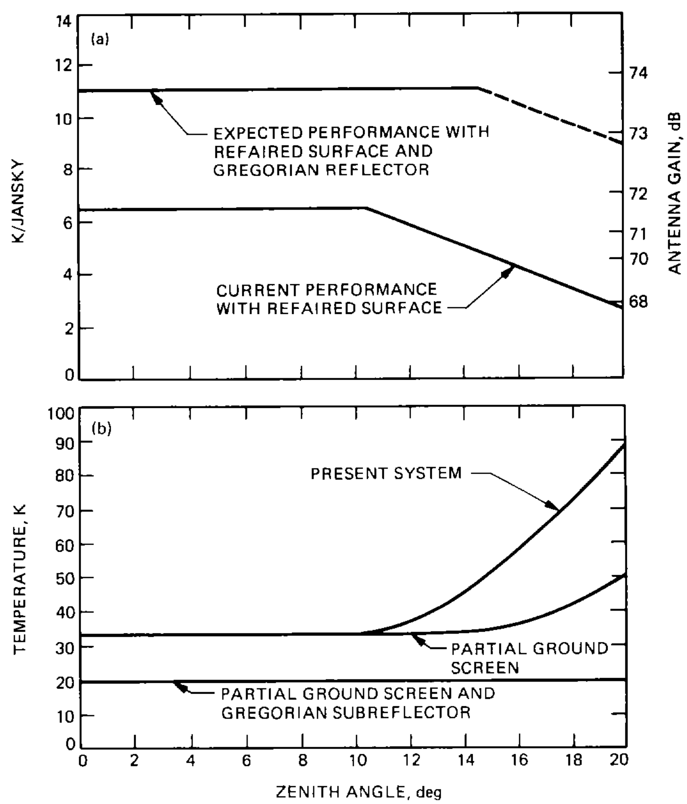

Fig. 2. Arecibo (a) antenna gain and (b) system temperature versus zenith angle for current conditions, the partial ground screen, and the Gregorian feed

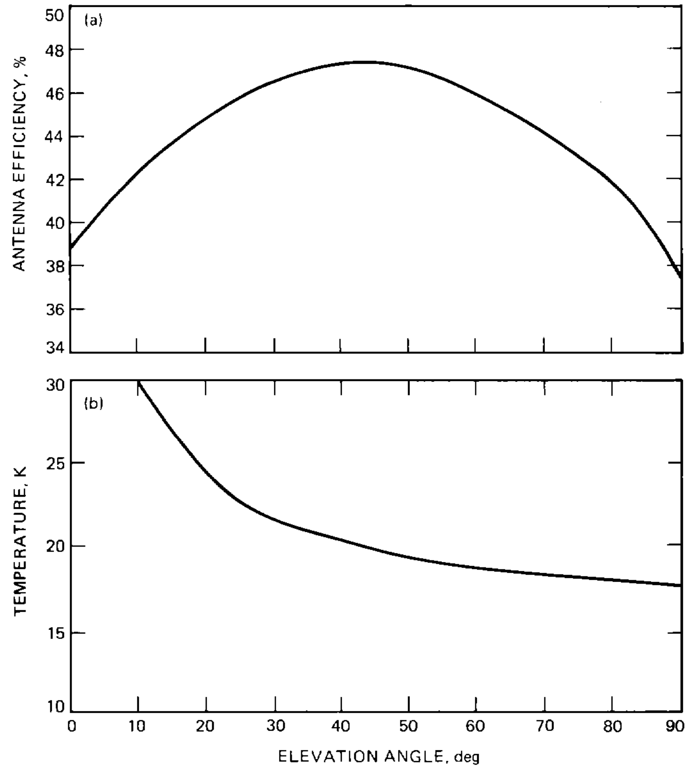

Fig. 3. Goldstone 3.5-cm (a) antenna efficiency and (b) system temperature versus elevation angle for current conditions. For the upgraded 70-meter antenna, a peak efficiency of 0.62 was assumed, with the same variation versus elevation angle as that shown above.

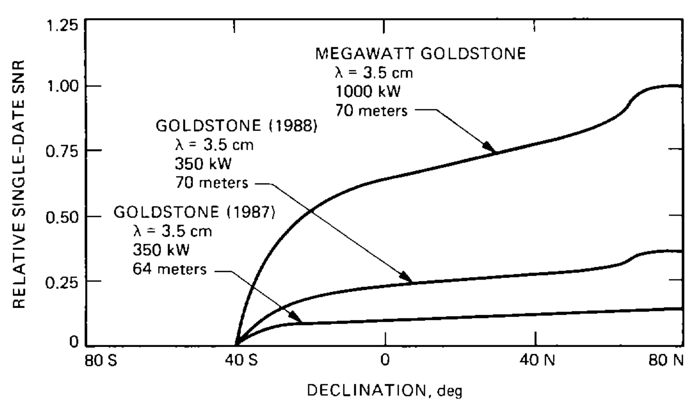

Fig. 4. Relative earth-based radar sensitivities for the Goldstone 3.5-cm radar, accounting for the already completed 64-meter to 70-meter aperture expansion and the proposed increase in transmitter power from 350 to 1000 kW

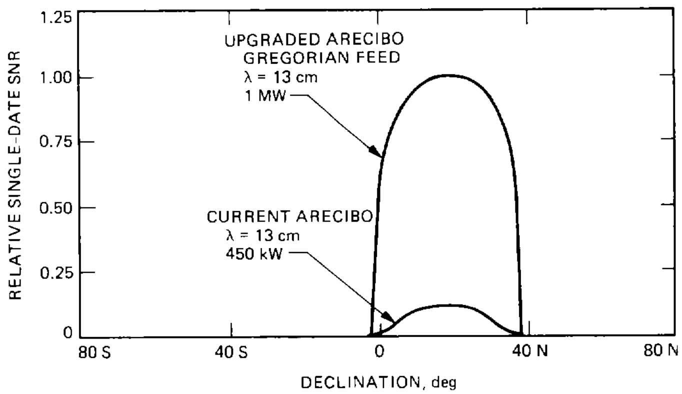

Fig. 5. Relative earth-based radar sensitivity for the Arecibo 12.6-cm radar for current and proposed Gregorian feed and transmitter improvements

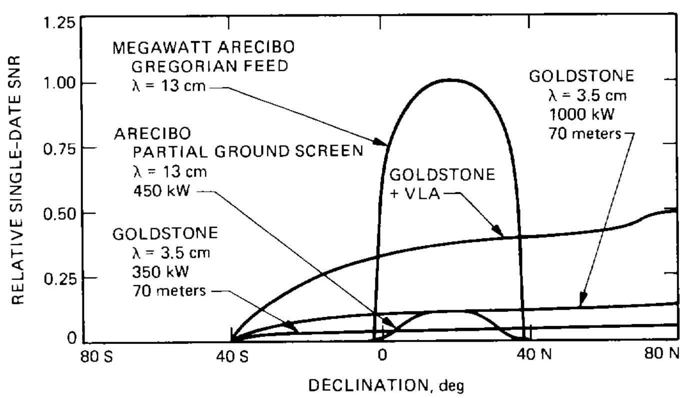

Fig. 6. Relative earth-based radar sensitivities for the Arecibo 12.6-cm radar in the 1980s and 1990s (before and after the Gregorian feed and increased transmitter power) as well as the Goldstone 3.5-cm radar in the 1990s (after the already completed aperture increase and the proposed increase in transmitter power)