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Intercontinental bistatic radar observations of 6489 Golevka (1991 JX)

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Abstract. Unlike the major planets and main belt asteroids, some near-Earth objects (NEOs) make their closest approaches to Earth at high northern declinations and therefore are visible simultaneously from North America, Europe and/or Asia, providing occasional opportunities for intercontinental radar experiments. The first celestial target of intercontinental radar was the Earth-crossing asteroid 6489 Golevka (1991 JX), which in June 1995 passed 0.034 AU from Earth at a declination of ~40 deg. High power (~0.5 MW), continuous-wave signals at 3.5 cm wavelength were transmitted toward the asteroid from the 70 m antenna at the JPL/NASA Goldstone Deep Space Communication Complex (DSCC) in California on 13, 14 and 15 June 1995 during several hours on each date. This illumination of the asteroid created an artificial radio source for astronomers anywhere on the asteroid-facing side of Earth. Five astronomical groups tried to detect the radar echoes and two succeeded. Detections were obtained on each of the three days by the 70 m antenna at Evpatoria DSCC in Crimea and on June 15 by the 34 m antenna at Kashima Space Research Center in Japan. The Goldstone 34 m antenna monitored echoes throughout all the observations. From the results of the Goldstone–Evpatoria experiment it can be inferred that the asteroid is about 0.5 km across, is not very elongated, possesses considerable surface irregularity and is very reflective presumably due to a large near-surface bulk density. This first intercontinental radar astronomy experiment can be considered as an initial step toward a global radar network for routine NEO investigations. © 1997 Elsevier Science Ltd

Listen here!
Surely, if the stars are lit—
There is somebody who longs for it?

Vladimir Mayakovsky, 1913

Introduction

Near-Earth asteroid 6489 Golevka (1991 JX) was discovered by E. F. Helin on May 9, 1991, with the 0.46 m Schmidt telescope at Palomar Observatory, U.S.A. Radar echoes from Golevka were obtained soon thereafter, on June 5, 1991 at Arecibo and on June 14, 1991 at Goldstone. The 1991 radar observations of 1991 JX indicated a radar cross section, echo bandwidth and delay depth of about 0.1 km^2, 13 Hz and 3 μs, respectively (Ostro *et al.*, 1991). Optical and radar astrometry yielded an accurate orbit and reliable predictions of the circumstances of the next apparition, in June 1995 (Yeomans *et al.*, 1992): a close approach (0.034 AU) at large positive declination (+40 deg). These features provided simultaneous visibility from North America and Europe or Asia, and the possibility of detecting echoes from Goldstone trans-

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Table 1. Radar system parameters

Goldstone transmitter (DSS-14)	
Central frequency	8510 MHz
Continuous power	475 kW
Antenna diameter	70 m
Antenna gain[a]	74.2 dB
Goldstone receiver (DSS-13)	
Antenna diameter	34 m
Antenna gain[a]	68.3 dB
System temperature	14 K
Evpatoria receiver (RT-70)	
Antenna diameter	70 m
Antenna gain[a]	74.0 dB
System temperature:	
at elevation of 90 deg	56 K
at elevation of 30 deg	72 K
at elevation of 15 deg	90 K
Kashima receiver	
Antenna diameter	34 m
Antenna gain[a]	65.4 dB
System temperature	56 K

[a]At elevation of 45 deg.

missions with instrumentation much less sensitive than the Arecibo and Goldstone systems. At the XXIInd IAU General Assembly in the Hague, Zaitsev and Ostro (1994) proposed that an intercontinental radar astronomy experiment be attempted, with Goldstone furnishing the transmissions and invited participation by other scientists. Ultimately astronomers attempted reception at six observatories—Goldstone, Evpatoria, Kashima, Bearlake (Russia), Usuda (Japan) and Weilheim (Germany)—but only the first three obtained echoes. Ostro *et al.* (1995) give an overview of all monostatic and bistatic observations, and Koyama *et al.* (1996) discuss the Goldstone–Kashima experiment. Here we report results of the Goldstone–Evpatoria experiment.

Observations

Table 1 lists nominal parameters of the transmitting and receiving systems used in the successful intercontinental observations. Goldstone radiated an unmodulated, continuous-wave (cw), circularly polarized signal with extremely fine frequency stability (on the order of a microhertz over several hours).

The Evpatoria receiver used hydrogen masers for all frequency synthesis. Before the observations, we carried out calibrations of the Evpatoria antenna using radio sources 3C123 and CAS-A. All reception was in the opposite circular (OC) polarization from that transmitted.

Table 2 lists observation parameters for all three days of observations. The transmitted frequency was 8510.00 MHz exactly in the case of the Evpatoria receiver station and $8510 + D(t)$ in the case of the Kashima receiver station, where $D(t)$ is an a priori predicted Doppler shift designed to place Goldstone–Usuda echoes at 8510 MHz. Koyama *et al.* (1996) applied an a posteriori differential (Kashima–Usuda) correction to co-register the Kashima echoes in frequency.

To avoid spectral smearing of the Evpatoria echoes, we continuously tuned the receiver to the echo frequency predicted by an orbital ephemeris, using a polynomial Doppler ephemeris synthesizer. The prediction ephemeris was based on an orbital solution that incorporated 254 optical, 19 delay and 11 Doppler measurements at arc 1991 Apr 15–1995 Jun 8 (Yeomans, 1995a). The Evpatoria receiver used the essential part of existing 6 cm planetary radar equipment, from the first intermediate frequency (IF1 = 310 MHz) through analog-to-digital converters

Table 2. Intercontinental observations

Receiver (RCV) station:	Evpatoria	Evpatoria	Evpatoria	Kashima
Date:	June 13	June 14	June 15	June 15
UTC RCV interval:	05:55–08:55	06:25–09:00	06:45–09:45	15:24–17:55
Transmission:				
Power (kW)	475	474	475	475
Frequency (MHz)	8510	8510	8510	$8510 + D(t)$
Polarization	Right	Right	Right	Left
RCV polarization:	Left	Left	Left	Right + Left
Asteroid:				
Right ascension (h)	21.3	21.8	22.2	22.3
Declination (deg)	+39	+38	+37	+36
Distance (Gm)	6.0	6.5	7.0	7.2
Phase interval[a] (deg)	322–153	356–102	20–211	182–342
Aspect angle (deg)	31	28	26	25.6
Echo:				
Ave. time delay (s)	40	43	47	48
Ave. Doppler shift (kHz)	−270	−309	−343	−355

[a]Phase interval and aspect angle were calculated for the following sidereal spin vector: ecliptic longitude = 340 deg, ecliptic latitude = 20 deg and spin period = 6.025 h (Hudson and Ostro, 1995). The zero longitude meridian of Golevka was defined as lying in the plane which contains the spin axis and the ray from the center of the asteroid to the vernal equinox of J2000.0 at the corresponding time (JD2451545.0). We define the origin of rotation phase to coincide with that plane's intersections with the Earth.

and the data acquisition system (Zaitsev and Petrov, 1993). Equipment added for this experiment included a 3.5 cm low noise amplifier and a down converter to IF1.

Doppler astrometry

Our spectra from each day showed echoes centered about 2 Hz from the ephemeris prediction. We experimented with two *ad hoc* approaches to estimate the echo center frequency (Ostro *et al.*, 1989). The first one averages the left and right spectral edge frequencies defined as the innermost drops of echo power to one standard deviation, i.e. the center frequency is $f_0 = (f_- + f_+)/2$. The second method fits a model of the form:

$$S(f) = S_0(1-(2(f-f_0)/B)^2)^{0.5n}$$

where B is limb-to-limb bandwidth and n a shape parameter (Jurgens and Bender, 1977). We have chosen to rely on the second method (Fig. 1), because it yields about 20% less scatter (Fig. 2).

Absolute Doppler frequencies were calculated by adding $P(t)$ to the frequency $DS(t)$ of our Doppler synthesizer, as measured by a frequency counter. Table 3 presents the resulting Goldstone–Evpatoria Doppler astrometry for epochs near the beginning, midpoint, and end of each day's track. The residuals were calculated with respect to an a posteriori ephemeris based on Goldstone monostatic and bistatic (DSS-14/13) radar astrometry, the Goldstone–Evpatoria astrometry reported here, and all optical astrometry available through June 1995 (Yeomans, 1995b).

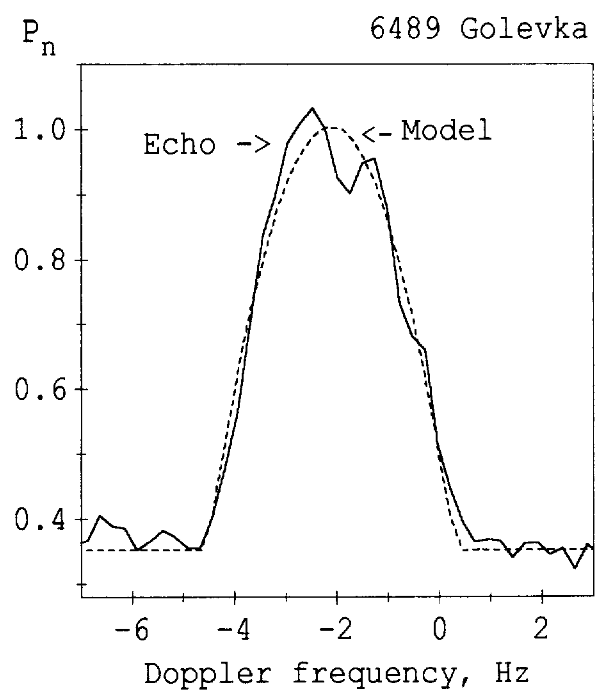

Fig. 1. A theoretical "$S(f)$" model spectrum (see text) fit to a 30 min sum of echo power spectra from June 13 Goldstone–Evpatoria data

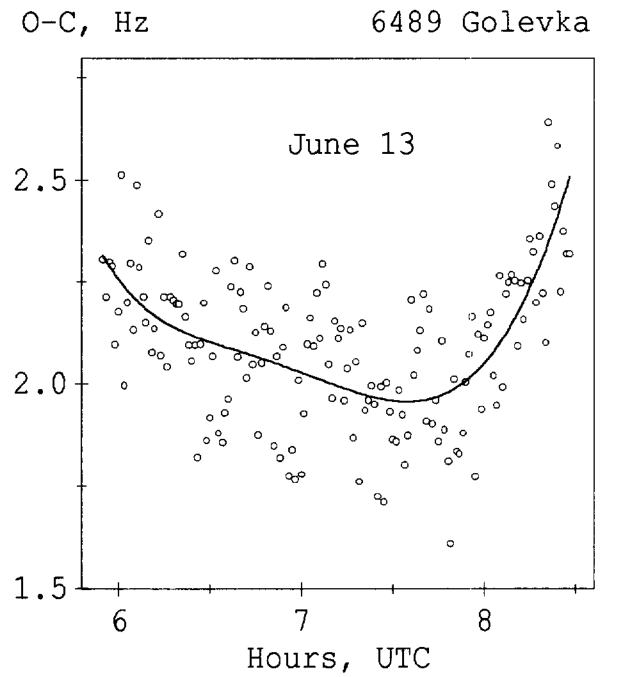

Fig. 2. Measurements (circles) of echo central frequency (f_0) with respect to the prediction ephemeris. The solid curve is a fifth-order polynomial fit, $P(t)$, to those points, each of which corresponds to a fit to a spectrum from a 1 min integration. The r.m.s. residual (OC) is about 0.14 Hz, corresponding to a radial velocity of 2.5 mm s^{-1}

Disc-integrated properties and its rotation variation

Prior to summing spectra over longer time intervals, the measured frequency drift $P(t)$ was compensated by multiplying the digital voltage samples by a complex factor $\exp[i\varphi(t)]$, where $\varphi(t)$ is a phase factor corresponding to $P(t)$. We then fast-Fourier-transformed the phase-rotated samples and formed power spectra. Figure 3 shows OC spectra at 0.244 Hz resolution for 15 10 min intervals on June 13. The sequence shows modest variation in spectral shape, some of which (e.g. a few of the more prominent peaks) might be due to irregularities in the asteroid's shape—Hudson and Ostro (1995) report that preliminary reconstruction of the asteroid's shape from delay-Doppler images shows it to be "a highly angular body, dominated by large, relatively flat facets joined at sharp ridges".

Figure 4 shows our measurements of OC radar cross section, σ_{oc}, as a function of subradar longitude (see cap-

Table 3. Goldstone–Evpatoria Doppler radar astrometry

UTC epoch of echo reception (hh:mm)	Doppler frequency (Hz)	Residual (Hz)
1995 Jun 13 06:00	−266,047.43 ± 0.32	0.11
1995 Jun 13 07:30	−270,367.96 ± 0.32	−0.09
1995 Jun 13 08:30	−273,261.01 ± 0.32	0.36
1995 Jun 14 06:30	−307,754.58 ± 0.40	−0.10
1995 Jun 14 07:30	−310,268.44 ± 0.40	−0.13
1995 Jun 14 08:50	−313,657.81 ± 0.40	0.15
1995 Jun 15 07:00	−340,848.03 ± 0.35	−0.15
1995 Jun 15 08:00	−343,076.37 ± 0.35	−0.05
1995 Jun 15 09:30	−346,442.72 ± 0.35	0.59

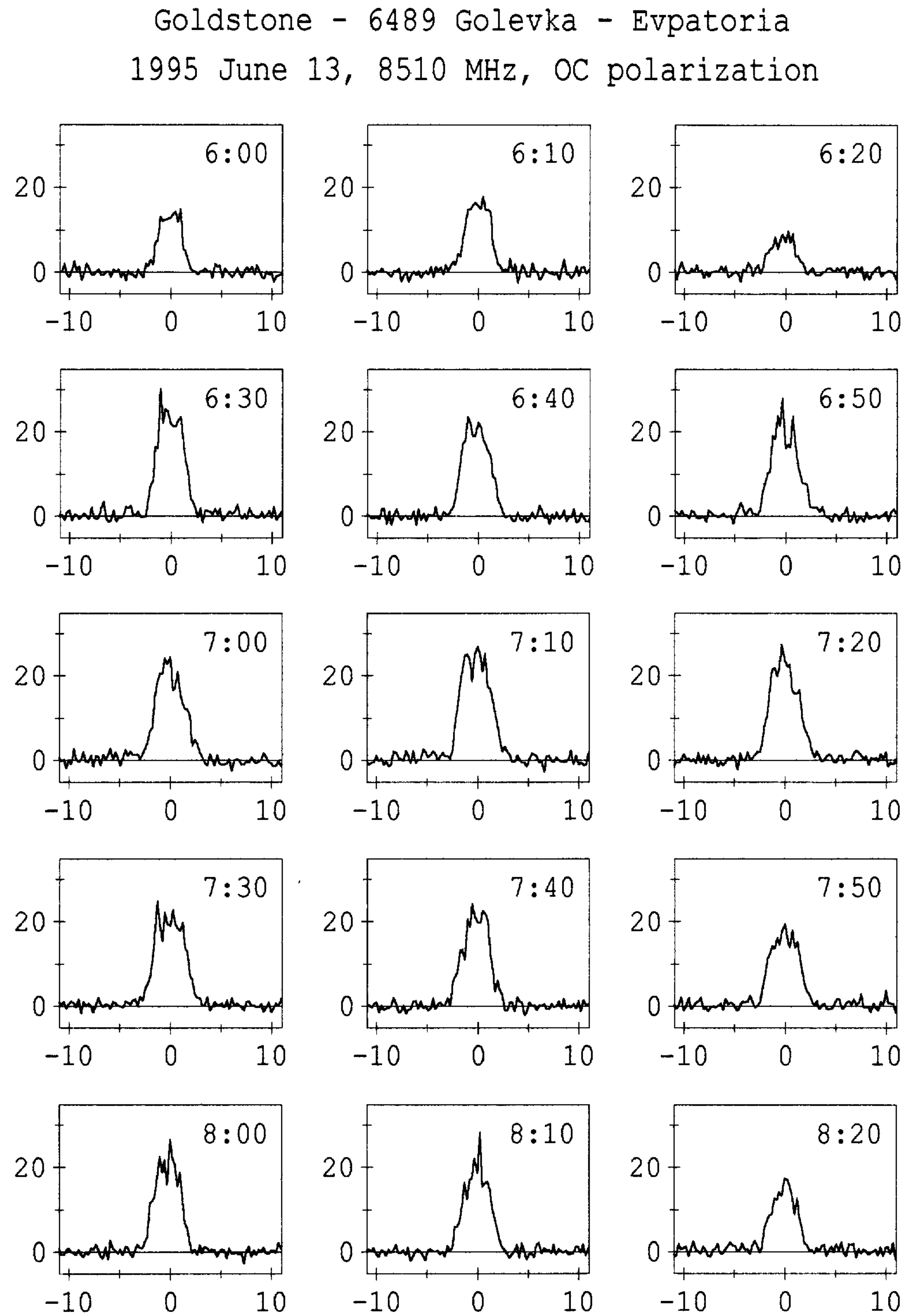

Fig. 3. Echo spectra for 15 10 min intervals, obtained in the OC polarization in Evpatoria, shown at a frequency resolution of 0.244 Hz. Echo power, in standard deviation of receiver noise, is plotted against Doppler frequency. The UTC midpoint of each interval is indicated

tion to Table 2). Our estimates range from 0.03 to 0.055 km^2 and average 0.038 km^2. Whereas the aspect angle apparently decreased during June 13–15 from 31 to 26 deg (Table 2), there is reasonably good agreement between results for those days.

The rotational variations of radar cross section are presumably due to shape irregularities at various scales. Our estimate of the average value of σ_{oc} is about half as large as the Goldstone–Kashima result (Koyama *et al.*, 1996), which agrees closely with a 13 cm estimate obtained at Arecibo in June 1991 (Ostro *et al.*, unpublished). The source of this inconsistency may become clear upon completion of analysis of Goldstone-only results.

Figure 5 shows three single-date spectral sums normalized to their individual peak values. The monotonous decrease of aspect angle is responsible for the day-to-day

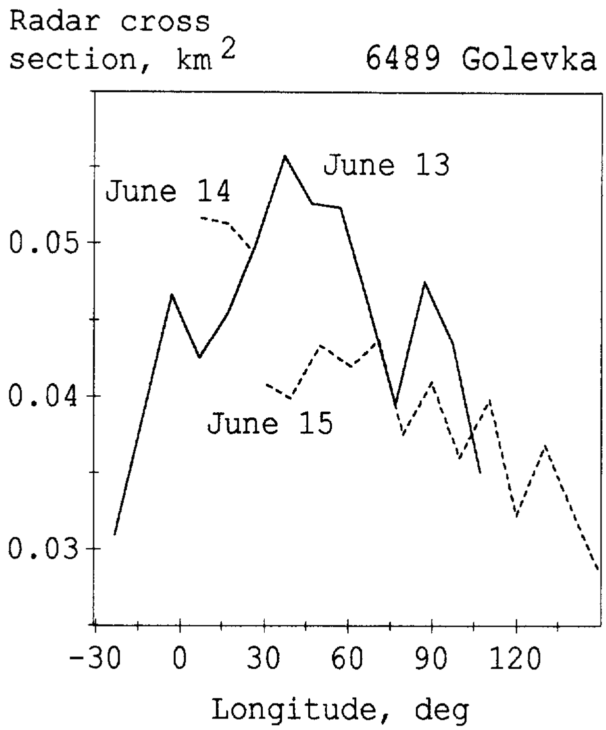

Fig. 4. Radar cross section versus longitude of subradar point. We discarded estimates from June 14 after 10:00, when echo strength dropped, perhaps due to tracking problems

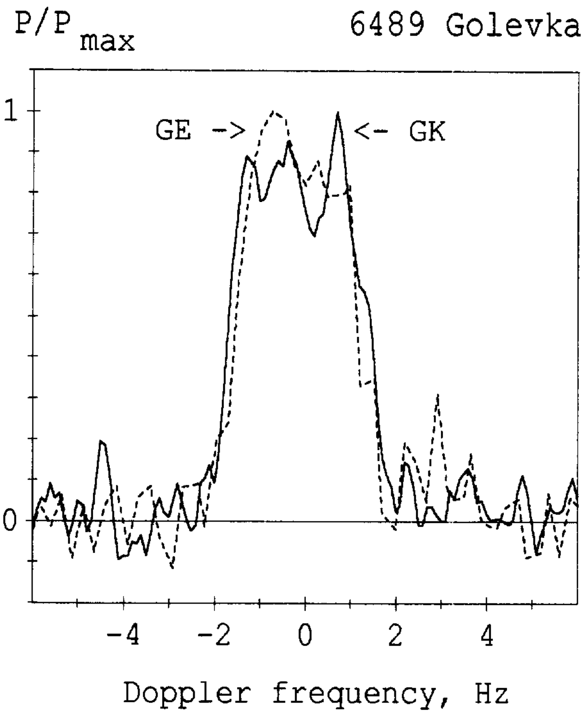

Fig. 6. Echo spectra obtained with Goldstone–Evpatoria (G–E) and Goldstone–Kashima (G–K) radar systems at rotational phase ~180 deg apart and nearly identical aspect angles ~26 deg with the pole direction that we have assumed (Table 2)

decrease in echo bandwidth. There is excellent agreement (within the intrinsic noise) between the bandwidths of the June 15 Evpatoria and Kashima spectra (Koyama *et al.*, 1996) taken roughly 1.5 rotations apart (Fig. 6).

Our estimates of echo bandwidth B show variations with rotation phase (Fig. 7) that are similar in magnitude to the radar cross section variations in Fig. 4. Echo bandwidth is related to D, the asteroid's apparent (plane-of-sky) extent orthogonal to the projected pole b:

$$B = (2\omega D/\lambda)\sin\alpha \quad (1)$$

where ω, α and λ are the apparent spin rate, aspect angle and wavelength, respectively. Relying on the pole direc-

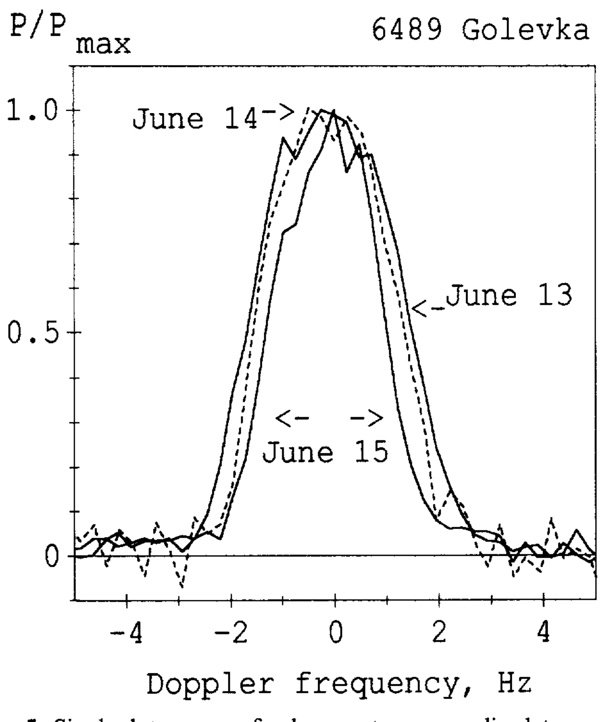

Fig. 5. Single-date sums of echo spectra, normalized to peak power

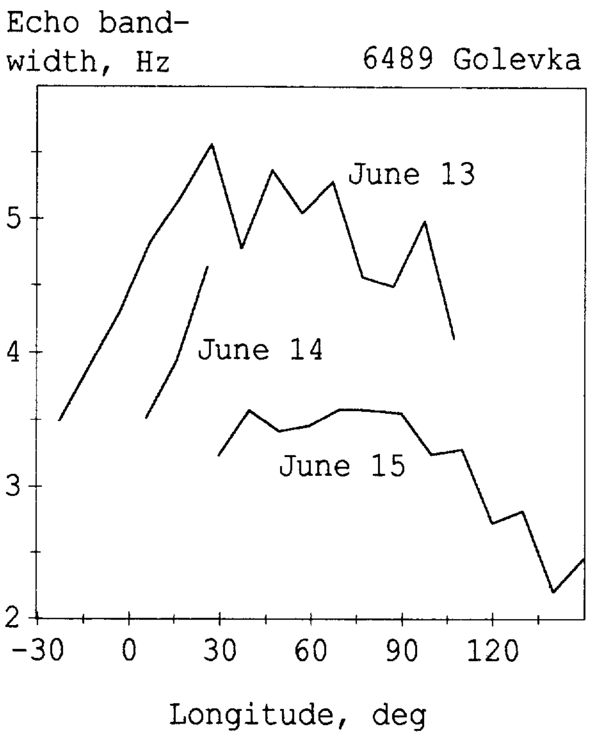

Fig. 7. Echo bandwidth variations due to rotation and day-to-day decrease of aspect angle

tion given in the caption of Table 2, we obtain the following estimates of the maximum, minimum and average values of D in meters: $D_{max} = (650 \pm 60)$, $D_{min} = (410 \pm 60)$, $D_{ave} = (560 \pm 60)$ for June 13; and $D_{max} = (500 \pm 70)$, $D_{min} = (305 \pm 70)$, $D_{ave} = (440 \pm 70)$ for June 15. (The uncertainties quoted for D do not take account of the uncertainty in the spin vector.)

If we take D as an equivalent sphere's diameter and divide our radar cross sections by $\pi D^2/4$, we obtain estimates of the OC radar albedo $4\sigma_{oc}/\pi D^2 = 0.18$, 0.24 and 0.25 for June 13, 14 and 15, respectively. These values are 1.5–2.0 times larger than typical albedoes for S-class main belt asteroids ($\sim$0.14 (Ostro *et al.*, 1985)) and values estimated for the S-class NEAs 4769 Castalia ($\sim$0.12 (Hudson and Ostro, 1994)) and 1620 Geographos ($\sim$0.13 (Ostro *et al.*, 1996)). We conclude that the bulk density of Golevka's surface is larger than that on "typical" S-class asteroids (or C-class asteroids, which tend to be less reflective than otherwise similar S-class objects (Ostro *et al.*, 1985)) and that the surface is unlikely to be very porous.

The hull estimation

A method for using spectra acquired at many rotational phases to obtain a two-dimensional shape constraint was introduced by Ostro *et al.* (1988) and first applied to 433 Eros (Ostro *et al.*, 1990). This technique ignores the functional form of the echo spectra, and uses the extent of those spectra to determine the convex envelope, or hull, of the asteroid's polar silhouette—a pole-on projection of the asteroid with concavities "filled in". This approach follows naturally from the geometric relation between spectral edge frequencies and the projection of the asteroid's shape onto its equatorial plane.

To estimate Golevka's hull we used only our strongest data, from June 13. We worked with 154 echo spectra, which have the raw frequency resolution $\sim$0.244 Hz. The integration time per spectrum was 60 s, during which Golevka rotated by $\sim$1 deg. The spectral elements have units of standard deviations of the receiver noise. The value of the standard deviation can be assumed to be constant for any given spectrum, but slightly varies between spectra because of variations in radar system sensitivity. The Doppler shift caused by the motion of the center of mass of the asteroid relative to the observing site was removed and we have assumed that the Doppler frequency zero corresponding to echoes from the center of mass. This assumption simplified our analysis, but may have introduced distortion into our hull estimate (Ostro *et al.*, 1988).

Golevka's synodic spin period during the radar observation was 6.025 h and the asteroid-centered declination of the radar was 31.4 deg. We assume that α was constant throughout the sequence, because α changed by less than 0.4 deg during this radar observation. Substituting these values into (1) yields a conversion factor of $y = 8.62\,\text{Hz}\,\text{km}^{-1}$ and an asteroid's instantaneous echo power spectrum has a bandwidth given by $B = yD$, where D is the sum of the distances d_+ and d_- from the plane containing the asteroid's apparent spin vector and the line of sight to the surface elements with the greatest positive (approaching) and negative (receding) radial velocities.

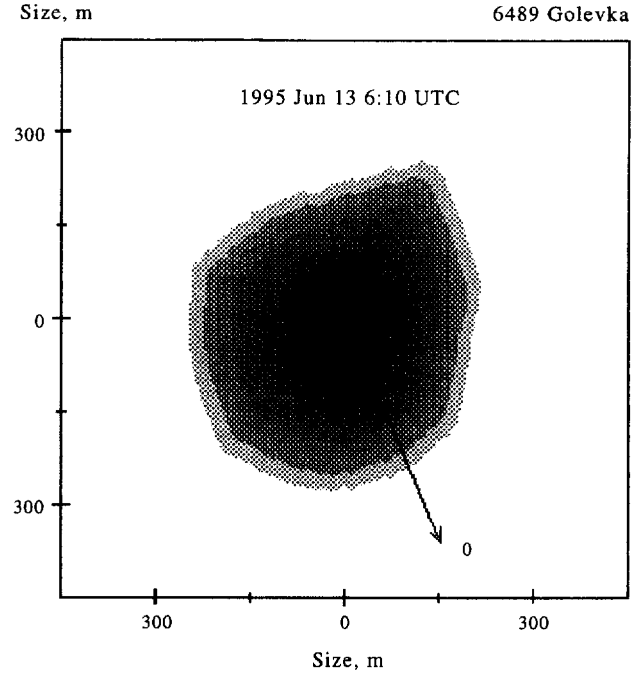

Fig. 8. Convex hull and sizes of Golevka's polar silhouette obtained from extent of the spectra. Earth's direction is toward the bottom of the figure. The asteroid rotates clockwise. The arrow is drawn from the rotation center at zero longitude

The best way of estimating the spectral edge frequencies is not known, but it is known that with SNR that low, estimating the hull from the raw spectra would be very inaccurate. To overcome the low SNR of the Golevka spectra, we determined sums of the echo spectra within 28 9 deg wide overlapping windows. The resulting 28 spectra have SNR near 20 and rotation phase resolution of 5 deg. We use the two standard deviation crossing as the values of d_+ and d_- associated with a spectrum taken at a rotation phase interval of 5 deg. This edge estimator might introduce systematic uncertainty into the hull estimation (Ostro *et al.*, 1988). Application of the geometric relation between spectral edge frequencies and the projection of the asteroid's shape onto its equatorial plane to 28 spectra yielded the hull estimate in Fig. 8. The extreme dimensions of Golevka's hull are $D_{max} = 560$ m and $D_{min} = 440$ m.

Summary and future prospects

The Goldstone–Evpatoria (G–E) data, considered alone, offer joint constraints on Golevka's dimension and spin vector. Taking advantage of the independent determination of the spin vector, we were able to infer that the asteroid is about half a kilometer in overall dimension, is not very elongated, possesses considerable surface irregularity, and is very reflective, presumably due to a large near-surface bulk density.

Now the G–E bistatic system is roughly 80% as sensitive (per unit of integration time) as the Goldstone-only (DSS-14/DSS-13) bistatic system. This is mainly because of a helium-cooled ruby-maser amplifier in the DSS-13 receiving system while Evpatoria used a less sensitive nitrogen-cooled HEMT-amplifier, as well as a nonoptimal four-reflector configuration of the Evpatoria antenna in the receiving mode. The echo strength achieved for Golevka was high enough for a more extended observation period to have yielded much more interesting information, but the common view period at Golevka's most northern position was only about 3.5 h. Perhaps future G–E observations can take advantage of NEO close approaches that occur higher in the northern sky: the G–E common view period increases to 15 h at declination 60 deg and becomes 24 h at declinations above 75 deg. More informative observations with the G–E system would use time-modulated waveforms to achieve resolution of echoes in time delay as well as in Doppler frequency (Ostro, 1993). However, such experiments are currently precluded by incompatibilities between Goldstone's transmit waveforms and Evpatoria's data-acquisition system.

Dedicated NEO radar telescope

The inauguration of intercontinental radar astronomy with the observations of Golevka was only the second asteroid radar experiment outside of the United States; the first was the Russia–Germany 1992 study of Toutatis using Evpatoria transmission and Effelsberg reception (Zaytsev *et al.*, 1993). The G–E observations marked the first detection of asteroid echoes by a Russian antenna and the G–K observations marked the beginning of planetary radar astronomy in Japan (Koyama *et al.*, 1996). The goal of worldwide development of radar astronomy calls for dedicated, more powerful tools. It should be stressed that no existing radar system has been designed specially for the needs of radar astronomy. Besides, these facilities are mainly occupied with other programmatic priorities: space mission control (e.g. Goldstone and Evpatoria) and radio astronomy (Arecibo). Therefore, we advocate construction of a truly dedicated radar telescope.

We believe that the current state of radar technology would permit design of a telescope, consisting of two fully steerable antennas widely separated from each other, that would be ten times more sensitive than the upgraded Arecibo instrument and much more useful for NEOs. If located near the equator (Fig. 9), such an antenna could have access to almost the entire sky on any given day.

We estimate the cost of such a dedicated radar would be about $200M for a two-antenna telescope, comparable to the cost of a Discovery-class space mission and much cheaper than the cost of one launch of the Space Shuttle. This radar would do flyby-level imaging and 3-D reconstruction of thousands of the discoverable near-Earth asteroids and comets, as well as comprehensive radar investigations of planets, their satellites and rings, and hundreds of main belt asteroids.

Comparison of asteroid radar progress in America vs. the Old World (Table 4) argues for development of advanced radar astronomy capabilities beyond the U.S. It is natural to imagine that the first dedicated NEO radar telescope might be implemented as a European or joint European–Japanese project (Zaitsev, 1997).

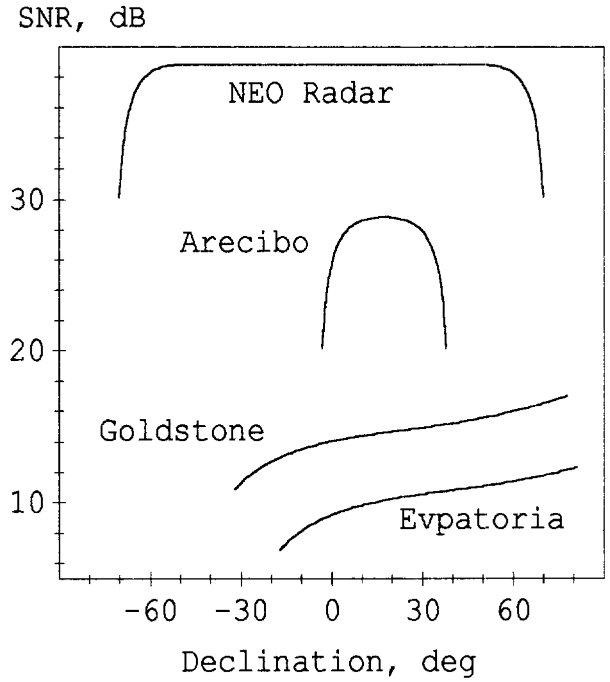

Fig. 9. Echo strength and sky coverage for Arecibo, Goldstone, and Evpatoria, compared to that of a proposed dedicated radar telescope. The signal-to-noise ratio is calculated for a typical kilometer-size asteroid at 0.1 AU

Table 4. The number of radar-detected asteroids and comets (up to mid 1996)

Celestial bodies	U.S.A.	Old World
Main belt asteroids	37	0
Near-Earth asteroids	39	2
Comets	6	0
Total	82	2

Acknowledgements. The success of this first intercontinental radar astronomy experiment would be impossible without substantial contributions by Goldstone, Evpatoria and Kashima personnel. We thank Eleanor F. Helin for proposing the name "Golevka" to the MPC of the IAU to honor the GOLdstone, EVpatoria and KAshima stations. Part of this research was conducted in Russia at the Institute of Radioengineering and Electronics under contract with the Ministry of Science and Technological Policy, and part was conducted in the United States at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, and at Communications Research Laboratory with support from Science and Technology Agency of Japan.

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