Goldstone Solar System Radar

Unique Capabilities of GSSR

[*Butrica,* 1996*; Ostro,* 1993; *Slade et al.,*1988b]

Full Sky Viewing

The 70 m antenna at the DSN facility at Goldstone, California (DSS-14) is fully steerable providing full-sky coverage of astronomical radar targets with up to 8 hrs tracking time. This provides superior coverage compared to the Arecibo facility which has limited pointing ability. Thus the GSSR can observe targets that Arecibo cannot see, such as certain Mars subradar regions valuable for landing site selection, Mars at opposition until 2005 and half of all Mercury inferior conjunctions. This full-sky coverage is also an important part of the GSSR's ability to contribute to Near-Earth Asteroid studies.

Dual Wavelength capacity

DSS-14 is equipped with both 3.5 cm (X-band) and 13 cm (S-band) transmitters and receivers for radar work. The 3.5 cm system is sensitive to smaller scales, and is thus useful for radar studies of cometary comas as well as planetary and asteroid surfaces. The 3.5 cm system is the more frequently used, however the 13 cm system offers an effective means to penetrate the Venus atmosphere, making the GSSR the only means for high-res topographic mapping of Venus. Furthermore, measuring the radar scattering behavior at different wavelengths provides better constraints on the scattering mechanisms. The Goldstone 13 cm system provides the only means for comparative analysis of wavelength scaling of surface terrain roughness until 2005, by which time two more rovers will have been dispatched to Mars and required to navigate across that terrain.

Bistatic Links

Transmitting at X-band, DSS-14 at Goldstone can and has been received in bistatic mode by recievers at DSS-13 (also at Goldstone), VLA (New Mexico), Evpatoria (Ukraine), Usuda, Kashima (Japan), VLBA. Bistatic experiments are also planned with the new Greenbank Telescope and the upgraded Arecibo. The bistatic experiments with the VLA provided full-disk images of Mercury, Mars and Venus, and discovered the polar deposits on Mercury. All of the radar detections of Titan to date have also been with the Goldstone-VLA bistatic link.

Interferometry

The Goldstone DSN facility has radar receivers at other antennas too. Antennas DSS-13, 15, 25 and 26 can be used at X-band, and DSS-13, 15, and 24 can be used at S-band. Using mutliple antennas at once allows the GSSR to function as the world's only multiple-baseline delay-Doppler interferometer. This offers allows the GSSR to resolve some of the north-south ambiguity inherent in delay-Doppler planetary radar observing. Interferometry is also uniquely capable of high-resolution topographic mapping, which has been most recently used to extend topographic information for the Moon beyond the latitudes observed by the Clementine mission.

GSSR Research Topics

Most GSSR Research Topics fall within the purview of NASA's Mission to the Solar System as defined by the Solar System Exploration Roadmap. The exceptions to this are the GSSR's relativity test experiments and observations of the Earth's stratosphere.

Mercury Orbit (Relativity Testing)

NASA Theme:	Structure and Evolution of the Universe
Status:	Ongoing radar experiments

Observations of Mercury are used for important tests of gravitational theory, Einstein's general theory of relativity, and other tests in physics. One experimental test of general relativity involves the advance of the perihelion of Mercury. If relativity holds, the perihelion will drift across the solar longitude at a very slow rate (a small fraction of one degree per century) rather than cross the classically predicted solar longitude on every revolution around the Sun. This test is performed by careful radar measurement of Mercury's orbit. A history of measurements has been established, and these data are compared with predictions to test the hypothesis. Another test of general relativity is the search for an increased delay of the echo return times of radio signals reflected from Mercury or Venus. Gravitational theories, including the hypothesis that the gravitational constant changes with time, are tested by measuring closure points, e.g., by repetitive high precision ranging to the same region on the surface of Mercury and removal of topographical time delay variations by differencing. Another test of this hypothesis seeks to determine the Sun's oblateness, i.e., the deviation of the shape of the Sun from that of a sphere.

Approximately ten legs of a Mercury closure point have been observed each year by the GSSR since 1990. The data set now contains more than 100 observations for which topographic profiles are available. The best data span more than 10 degrees either side of the sub-earth point along the apparent rotational axis. All longitudes are currently covered, and the latitudes span from -10 to +10 degrees. These data include locations that have been viewed up to four times over that period.

[*Jurgens et al.*, 1998a; *Jurgens et al.*, 1998b; *Slade et al.*, 1997; *Anderson*, 1996; *Slade et al.*, 1994; *Slade et al.*, 1993]

Mercury Surface Properties:

NASA Theme:	Formation and Dynamics of Earth-Like Planets
Status:	Ongoing analysis of existing and new data.

In 1969, radar data showed that the surface of the planet consisted of several large rough areas. Later, in 1972, radar observations at 2388 MHz revealed a cratered surface with up to 50-100 km crater sizes. In 1991, Goldstone-VLA 3.5 cm observations obtained full-disk images of Mercury via the technique of aperture synthesis. Maps were produced of areas not already studied by Mariner 10. Radar tracks in Mercury's equatorial regions obtained for the reltivity tests with closure points often have sufficient signal-to-noise levels to allow fitting of radar scattering models. The results of the models in turn allow an assessment of variations of surface roughness and material density that are related to the surficial geology of the planet.

[*Muhleman et al.*, 1995; *Butler*, 1994; *Butler et al.*, 1994; *Butler et al.*, 1993a; *Butler et al.*, 1992; *Harmon and Slade*, 1992a; *Slade et al.*, 1992b; *Slade et al.*, 1991]

Mercury Polar Studies:

NASA Theme: Formation and Dynamics of Earth-Like Planets
Status: GSSR Full-disk imaging planned 1998/1999

Perhaps the most unexpected discovery of planetary radar astronomy in the last decade was the polar deposits on Mercury. First observed using the Goldstone-VLA bistatic aperture synthesis imaging technique, and later confirmed by Arecibo, the radar-bright regions at Mercury's poles behave like Mars' south polar cap and the Galilean satellites, strongly suggesting that they are composed of ice. Thermal modelling in conjuction with detailed radar mapping suggests that the deposits are in fact protected ices lying in permanently shadowed craters. Future upgrades to the data acquisition system will allow further study: plans to allow random-long-code experiments should allow full-disk imaging with opportunities to re-observe the polar regions when the orbital parameters are appropriate.

[*Muhleman et al.*, 1995; *Butler*, 1994; *Harmon et al.*, 1994; *Muhleman et al.*, 1994; *Butler et al.*, 1994; *Butler et al.*, 1993a; *Harmon et al.*, 1993; *Slade et al.*, 1992a; *Harmon and Slade*, 1992b; *Butler et al.*, 1992; *Harmon and Slade*, 1991]

Venus Surface Properties:

NASA Theme: Formation and Dynamics of Earth-Like Planets
Status: Observations are being planned for 1998-1999.

Goldstone radar observations of the equatorial plains of Venus provide complementary information to that obtained by Magellan. Different radar scattering mechanisms dominate each system, leading to a sampling of different surface properties. Comparison of image data and derived parameters indicate for example that relatively high dielectric constants on impact-related parabolic features are detected in Goldstone backscatter, Magellan reflectivity, and Magellan emissivity data; the dielectric effects are overwhelmed by roughness-related signatures in Magellan synthetic aperature radar (SAR) data. Scattering properties of an equatorial "ridge belt" structure suggest highly weathered or soil-dominated surfaces.

Goldstone-VLA bistatic observations have provided dual-polarization full-disk images which confirm the high-reflectivity mountain-tops in several Venusian highlands. The scattering properties at X-band are compatible with either volume scattering or multiple surface-scattering from a rough surface.

[*Haldemann*, 1997; *Haldemann et al.*, 1997c; *Haldemann et al.*, 1995a; *Plaut and Arvidson*, 1992; *Tryka et al.*, 1991; *Plaut et al.*, 1990; *Jurgens et al.*, 1990; *Senske*, 1990]

Venus Geophysics:

NASA Theme: Formation and Dynamics of Earth-Like Planets
Status: Observations are being planned for 1998-1999.

The GSSR provides information on the spin-state of Venus, which is an important input parameter for spacecraft studies, as well as a constraint on planetary geophysical parameters.
Additionally, the ability to distinguish different terrains and topographic information from radar images allows interpretation of the regional-scale deformation that is part of

Venus' crustal evolution. Structural analysis has been performed with classical remote-sensing methods. Folds and faults identified on radar images were reported on a structural map. Their type and distribution allowed to define the style of the crustal deformation and the context in which these structures formed.

[*Ansan and Vergely*, 1995; *Ansan et al.*, 1994; ; *Slade et al.*, 1990 *Arvidson et al.*, 1989; *Slade et al.*, 1988a; *Slade et al.*, 1987]

Stratospheric Studies:

NASA Theme: Mission to Planet Earth
Status: No new observations planned at this time

The NASA/JPL Goldstone planetary radar has been succesfully used to study the Earth's atmosphere. With its high bandwidth and power, it can achieve a height resolution of 20 m, which is significantly better than the usual 150 m resolution for stratospheric radars. A very thin scattering layer that persisting over several hours at the same height just above the tropopause has been observed, along with a the two-minute oscillation observed in the vertical velocity.

[*Cho et al.*, 1996a; *Cho et al.*, 1996b; *Cho et al.*, 1995]

Lunar Polar Observations:

NASA Theme: Formation and Dynamics of Earth-Like Planets
Status: 1997 and 1998 observations are being analyzed

Recent spacecraft missions to the Moon have still left the topography of the lunar polar regions largely unknown. Detailed topographic maps of the Moon are needed for : 1) Improving current global models for the topography of the Moon, 2) Investigating the possible presence of volatiles at the poles, which requires adequate digital elevation models in order to locate permanently shadowed areas, 3) Understanding lunar basins and lunar internal structure.

Interferometric SAR techniques can yield the topography of the polar regions of the Moon using the NASA/JPL GSSR. DSS-14 is used to transmit at 3.5 cm wavelength while two nearby 34 m antennas (DSS-13, 15, 25 or 26) are used to form a receive interferometer. In this interferometric mode, heights above a reference surface can be derived from the relative phase between the two radar signals. A focused delay-Doppler processing is used to generate backscatter maps with a surface resolution of 75 m. The phase information is expected to yield surface heights at a similar resolution.

[*Margot et al.*, 1998; *Margot et al.*, 1997]

Mars Surface Properties:

NASA Theme: Formation and Dynamics of Earth-Like Planets
Status: Planning for observations during the 1999 Mars opposition.

Delay-Doppler as well as Doppler-only (or continuous-wave, CW) observations of Mars have been a mainstay of Martian radar studies since Mars was first detected in the sixties. Models of Mars' radar scattering have been developped based on the accumulated observations. Different geologic provinces display distinct radar properties that relate to the roughness, dustiness or rockiness of the surface. Full disk images of

Mars were obtained with the Goldstone-VLA bistatic system at 3.5 cm wavelength. The reflected energy was mapped in individual 12-minute snapshots with the VLA in its largest configuration. The images reveal near-surface features including a region in the Tharsis volcano area that displayed no echo to the very low level of the radar system noise. The feature, called Stealth, is interpreted as a deposit of dust or ash.

We are developping new data collection techniques that should overcome the constraints of previous experiments that limited the incidence angle coverage to +/- 6 degrees from nadir. The new random long-code technique will be tested during the 1999 Mars opposition and combined with interferometric observations should yield full dist radar images of Mars.

[*Slade et al.*, 1998; *Slade*, 1997; *Muhleman et al.*, 1995; *Slade and Jurgens*, 1994b; *Slade et al.*, 1994c; *Butler*, 1994; *Butler et al.*, 1993b; *Butler et al.*, 1992; *Thompson et al.*, 1992; *Harmon et al.*, 1992a; *Harmon et al.*, 1992b; *Simpson et al.*, 1992; *Slade et al.*, 1991b; *Jurgens et al.*, 1991; *Moore et al.*, 1991; *Moore and Thompson*, 1991; *Muhleman et al.*, 1991; *O'Brien et al.*, 1991; *Harmon and Slade*, 1989; *Butler et al.*, 1989]

Martian Polar Studies:

NASA Theme: Formation and Dynamics of Earth-Like Planets
Status: Planning for observations during the 1999 Mars opposition

The strongest reflecting geologic region observed in the Mars Goldstone-VLA bistatic experiment was the south polar ice cap, which was reduced in size to the residual south polar ice cap at the season of observation. The cap image is interpreted as arising from nearly pure CO_2 or H_2O ice with a small amount of martian dust (less than 2 percent by volume) and a depth greater than 2 to 5 m.

The polar regions are not usually observed with delay-Doppler experiments. However, the random-long-code technique planned for 1999 and beyond will allow range data to be collected up to the poles, allowing us to study the evolution of the Martian polar deposits with time through and opposition. The north polar deposits, indistinctive in the radar observations with Goldstone/VLA will be observed in 1999.

[*Slade et al.*, 1998; *Butler et al.*, 1995; *Muhleman et al.*, 1995; *Butler*, 1994;*Butler et al.*, 1993b; *Butler et al.*, 1992; *Muhleman et al.*, 1991; *Slade et al.*, 1989]

Mars Geophysics:

NASA Roadmap: Formation and Dynamics of Earth-Like Planets
Status: Analysis of existing topographic profiles ongoing at various institutions.

Topographic profiles provided by the ranging portion of any Mars delay-Doppler radar experiment with the GSSR can and have been used to analyze the dynamical behavior of the Martian crust. Topographic profiles of regional slopes and across craters can be used to constrain parameters in crustal relaxation models.

[*Slade et al.*, 1994; *Goldspiel et al.*, 1993; *Esposito et al.*, 1992; *Goldspiel et al.*, 1992; ; *Zisk et al.*, 1992*; Roth*, 1991; *Zisk et al.*, 1991]

Mars Landing Site Certification:

NASA Theme: Mars Exploration Support

Status: Work for 2001 landing site selection and comparison of radar results with MGS results. Observations planned 1999.

Goldstone radar information was first used to aid in landing site selection for the Viking 1 lander in 1976. Radar addresses relief, roughness and rockiness criteria for potential landing sites. The ranging profiles profided a measure of the relief across Mars Pathfinder's target landing ellipse, confirming that the chosen region was acceptable for Pathfinder's entry descent, and landing profile. Radar scattering models fit to the echoes provide parameters that can be interpreted for rockiness/dustiness and general roughness of the observed region. These parameters were in turn used to certify Pathfinder's landing site as safe for the airbags, and to decide that the area would be trafficable for the Sojourner rover. Similar analyses will be performed on existing and future Mars data in aid of NASA's ongoing Mars exploration. Topographic relief information will soon be available from the laser altimeter (MOLA) on the MGS orbiter at Mars. The radar tracks, perpendicular to MOLA's orbital tracks will be complimentary to the new data, and each set will be used to check the other.

[*Haldemann et al.*, 1998; *Slade et al.*, 1998; *Haldemann*, 1997; *Haldemann et al.*, 1997a; *Haldemann et al.*, 1997b; *Slade et al.*, 1996; *Haldemann et al.*, 1995b; *Slade et al.*, 1995; *Slade and Jurgens*, 1994a]

Asteroids:

NASA Theme: Building Blocks and Our Chemical Origins

Status: Several asteroid observations planned each year, and as targets of opportunity arise.

Radar is a powerful source of information about asteroid physical properties and orbits. Measurements of the distribution of echo power in time delay (range) and Doppler frequency (radial velocity) can provide spatial resolution as fine as 10 meters if the echoes are strong enough. With adequate orientational coverage, such images can be used to construct geologically detailed three-dimensional models, to define the rotation state precisely, and to constrain the object's internal density distribution. Moreover, radar wavelengths are sensitive to near-surface bulk density and structural scales larger than a few centimeters.

Studies of the evolution of the error ellipse of the location of a near-Earth asteroid show that the addition of a few radar observations can greatly reduce the ephemeris uncertainties compared to the uncertainties from optical observations alone. Thus radar observations are crucial for obtaining an well-determined orbit for near-Earth asteroids.

[*Mitchell et al.*, 1998; *Benner et al.*, 1998; *Benner et al.*, 1997a; *Benner et al.*, 1997b; *Hudson, R. S., and S. J. Ostro*, 1997; *Zaitsev et al.*, 1997; *Mitchell et al.*, 1996; *Ostro et al.*, 1996a; *Ostro et al.*, 1996b; *Hudson, R. S., and S. J. Ostro*, 1995; *Ostro et al.*, 1995a; *Ostro et al.*, 1995b; *Ostro et al.*, 1995c; *Ostro et al.*, 1994; *Hudson, R. S., and S. J. Ostro*, 1994; *de Pater et al.*, 1994; *Ostro et al.*, 1993; *Hudson, R. S.*, 1993; *Ostro et al.*, 1991; *Yeomans et al.*, 1987]

Galilean Satellites:

NASA Theme: Formation and Dynamics of Earth-Like Planets

Status: No new observations currently planned.

Io, Europa, Ganymede, and Callisto, the four Galilean satellites of Jupiter, have all been observed by the GSSR. Ganymede, the largest of these, was first observed by the GSSR at 12.6-cm wavelength in 1974. The outer three of these moons are good radar reflectors. The radar echoes are extremely unusual when the polarization properties of the radar return are compared with those of the typical solar system echo, and are now taken to be signatures of the cold ice that dominates the surfaces of these worlds. More recently observations have been made at 3.5-cm wavelength.

[*Ostro et al.*, 1992]

Titan Properties:

NASA Theme: Building Blocks and Our Chemical Origins
Status: Observations planned October 1998

Radar echoes from Titan have to date been obtained with the Goldstone/VLA bistatic system. Statistically significant echoes were obtained that show Titan is not covered with a deep global ocean of ethane as previously thought. The cross-sections around 0.3 are high enough to suggest that the surface of the planet is icy and scatters similarly to the Galilean satellites. Future observations are planned with Arecibo transmit/Goldstone receive set of bistatic experiments, along with further Goldstone/VLA work. These studies of Titan's surface radar properties will provide the basis for the Cassisni mission's exploration of the planet.

[*Muhleman et al.*, 1998; *Muhleman et al.*, 1995; *Muhleman et al.*, 1993; *Muhleman et al.*, 1992; *Ostro et al.*, 1992; *Muhleman et al.*, 1989; *Muhleman et al.*, 1990]

Comet Studies:

NASA Theme: Building Blocks and Our Chemical Origins
Status: Ongoing as viewing opportunities arise.

Radar observations of comet Hyakutake (C/1996 B2) made with the GSSR detected echoes from the nucleus and from large grains in the inner coma. The nucleus of this bright comet was estimated to be only 2 to 3 kilometers in diameter. Models of the coma echo indicate backscatter from porous, centimeter-size grains ejected anisotropically at velocities of tens of meters per second. The radar observations suggest that a comet's activity may be a poor indicator of its size and provide evidence that large grains constitute an important component of the mass loss from a typical active comet.

[*Goldstein et al.*, 1984; *Harmon et al.*, 1997]

References

Anderson, J.D., Shape and Orientation of Mercury from Radar Ranging Data, *Icarus*, *124*, 690-697, 1996.

Ansan, V., and P. Vergely, Evidence of Vertical and Horizontal Motions on Venus - Maxwell Montes, *Earth Moon and Planets*, *69* (3), 285-310, 1995.

Ansan, V., P. Vergely, and P. Masson, Tectonic Interpretations of Central Ishtar Terra (Venus) from Venera-15/16 And Magellan Full-resolution Radar Images, *Planetary and Space Science*, *42* (3), 239-Continues, 1994.

Arvidson, R.E., J.J. Plaut, R.F. Jurgens, R.S. Saunders, and M.A. Slade, Geology of Southern Guinivere Planitia, Venus, Based on Analyses of Goldstone Radar Data, in *Lunar and Planetary Science XX*, pp. 575-576, LPI Publications Office, Houston TX, 77058-4399, Houston, Texas, 1989.

Benner, L., S.J. Ostro, and e. al., Radar Observations of Asteroid 2063 Bacchus, *Icarus* (submitted Feb. 18, 1998), 1998.

Benner, L.A.M., S.J. Ostro, D. Choate, C.R. Franck, R. Frye, J.D. Giorgini, S.D. Howard, R.F. Jurgens, D. Kelly, R. Rose, K.D. Rosema, M.A. Slade, R. Winkler, D.K. Yeomans, D.L. Mitchell, and R.S. Hudson, Radar Observations of Near-Earth Asteroid 2063 Bacchus, *29th DPS Meeting, Bulletin of the American Astonomical Society, 29*, 965, 1997a.

Benner, L.A.M., S.J. Ostro, J.D. Giorgini, R.F. Jurgens, D.L. Mitchell, R. Rose, K.D. Rosema, M.A. Slade, R. Winkler, D.K. Yeomans, D.B. Campbell, J.F. Chandler, and I.I. Shapiro, Radar Detection of Near-Earth Asteroids 2062-Aten, 2101-Adonis, 3103-Eger, 4544-Xanthus, and 1992-QN, *Icarus*, *130* (2), 296-312, 1997b.

Butler, B.J., D.O. Muhleman, and M.A. Slade, The Polar Regions of Mars: 3.5-cm Radar Images, *Icarus*, *114*, 679-706, 1995.

Butler, B. J., *Radar Investigations of Mars and Mercury: Planetological Implications*, Ph.D. thesis, California Institute of Technology (Caltech), Pasadena, 1994.

Butler, B.J., D.O. Muhleman, and M.A. Slade, VLA/Goldstone 3.5-cm Radar Observations of Mercury in 1994, *26th DPS Meeting, Bulletin of the American Astonomical Society*, *26*, 1106, 1994.

Butler, B.J., D.O. Muhleman, and M.A. Slade, Mercury: Full-disk Radar Images and the Detection and Stability of Ice at the North-pole, *Journal of Geophysical Research Planets*, *98* (E8), 15003-15023, 1993a.

Butler, B.J., D.O. Muhleman, and M.A. Slade, Results from 1992 and 1993 VLA/Goldstone 3.5 cm Mars Radar Data, *25th DPS Meeting, Bulletin of the American Astonomical Society*, *25*, 1040, 1993b.

Butler, B.J., D.O. Muhleman, and M.A. Slade, Comparison of the Radar Returns from the Icy Poles and Other Regions of Mars and Mercury, in *Lunar and Planetary Science XXIII*, pp. 191-192, Houston, Texas, 1992.

Butler, B.J., D.O. Muhleman, A. Grossman, and M.A. Slade, Global Radar Mapping of Mars: Surface and Subsurface, *EOS, Transactions, AGU*, *70* (43), 1171, 1989.

Butrica, A. J., *To See the Unseen, A History of Planetary Radar Astronomy*, NASA History Series, NASA History Office, Washington, D.C., 1996.

Cho, J.Y.N., R.F. Jurgens, and M.A. Slade, First Observation of the Earth's Atmosphere with the NASA/JPL Goldstone Solar System Radar, in *National Radio Science Meeting*, 1996a.

Cho, J.Y.N., R.F. Jurgens, and M.A. Slade, High-resolution Stratospheric Dynamics Measurements with the NASA/JPL Goldstone Solar-System Radar, *Geophysical Research Letters, 23*, 15, 1909-1912, 1996b.

Cho, J.Y.N., R.F. Jurgens, and M.A. Slade, High-resolution Observations of Stratospheric Dynamics with the NASA Goldstone SolarSystem Radar, in *IUGG Meeting*, 1995.

de Pater, I., P. Palmer, D.L. Mitchell, S.J. Ostro, D.K. Yeomans, and L.E. Snyder, Radar Aperture Synthesis Observations of Asteroids, *Icarus*, *111* (2), 489-502, 1994.

Esposito, P.B., W.B. Banerdt, G.F. Lindal, W.L. Sjogren, M.A. Slade, B.G. Bills, D.E. Smith, and G. Balmino, Gravity and Topography, in *Mars*, edited by H.H. Kieffer, B.M. Jakosky, C.W. Snyder, and M.S. Matthews, pp. 219-226, University of Arizona Press, Tucson, 1992.

Goldspiel, J.M., S.W. Squyres, M.A. Slade, R.F. Jurgens, and S.H. Zisk, New Radar-Derived Topography of Low Southern Latitudes of Mars, *Icarus*, *106*, 346-364, 1993.

Goldspiel, J.M., S.W. Squyres, M.A. Slade, R.F. Jurgens, and S.H. Zisk, New Radar-Derived Topography of Ancient Aqueous Sedimentation Basins on Mars, in *Lunar and Planetary Science XXIII*, pp. 423-424, Houston, Texas, 1992.

Goldstein, R. M., R. F. Jurgens, and Z. Sekanina. A radar study of comet IRAS-Araki-Alcock 1983d.*Astron. J. 89*, 1745-1754 (1984).

Haldemann, A.F.C., R.F. Jurgens, M.A. Slade, M.P. Golombek, H.J. Moore, and T. Blackmon, Mars Pathfinder Landing Site Radar Properties, in *European Geophysical Society XXXIII General Assembly*, Nice, France, 1998.

Haldemann, A.F.C., *Interpreting Radar Scattering: Circular Polarization Perspecitves from Three Terrestrial Planets*, Ph.D. thesis, California Institute of Technology (Caltech), Pasadena, 1997.

Haldemann, A.F.C., R.F. Jurgens, M.A. Slade, M.P. Golombek, and H.J. Moore, Mars Pathfinder Landing Site Radar Properties, *EOS, Transactions, AGU*, *78* (46), 1997a.

Haldemann, A.F.C., D.L. Mitchell, R.F. Jurgens, M.A. Slade, and D.O. Muhleman, Mars Pathfinder Landing Site Assessment with Goldstone Delay-Doppler and CW-radar Experiments, *Journal of Geophysical Research Planets*, *102* (E2), 4097-4106, 1997b.

Haldemann, A.F.C., D.O. Muhleman, B.J. Butler, and M.A. Slade, The Western Hemisphere of Venus: 3.5 Cm Dual Circular-polarization Radar Images, *Icarus*, *128* (2), 398-414, 1997c.

Haldemann, A.F.C., D.O. Muhleman, B.J. Butler, and M.A. Slade, Western Hemisphere of Venus: Goldstone-VLA Images of Beta Regio, *27th DPS Meeting, Bulletin of the American Astonomical Society*, *27* (3), 1077, 1995a.

Haldemann, A.F.C., D.O. Muhleman, R.F. Jurgens, and M.A. Slade, Assessment of Pathfinder Landing Site with Goldstone Radar Ranging and Goldstone-VLA Dual-Polarization Imaging, in *Mars Pathfinder Landing Site Workshop II: Characteristics of the Ares Vallis Region and Field Trips in the Channeled Scabland, Washington*, edited by M.P. Golombek, K.S. Edgett, and J.W. Rice, Jr., pp. 63, Lunar and Planetary Institute, 1995b.

Harmon, J.K., S.J. Ostro, L.A.M. Benner, K.D. Rosema, R.F. Jurgens, R. Winkler, D.K. Yeomans, Choate-D, Cormier-R, J.D. Giorgini, D.L. Mitchell, Chodas-PW, Rose-R, Kelley-D, M.A. Slade, and Thomas-ML, Radar Detection of the Nucleus and Coma of Comet Hyakutake (C/1996 B2), *Science*, *278* (5345), 1921-1924, 1997.

Harmon, J.K., M.A. Slade, R.A. Velez, A. Crespo, M.J. Dryer, and J.M. Johnson, Radar Mapping of Mercury's Polar Anomalies, *Nature*, *369*, 213-215, 1994.

Harmon, J.K., M.A. Slade, R. Velez, A. Crespo, and M. Dryer, New Radar Images of the Poles of Mercury, *Bulletin of the American Astronomical Society*, *25*, 1089, 1993.

Harmon, J.K., and M.A. Slade, Radar Mapping of Mercury, in *Lunar and Planetary Science XXIII*, pp. 485-486, Houston, Texas, 1992a.

Harmon, J.K., and M.A. Slade, Radar Mapping of Mercury: Full Disk Images of Polar Anomalies, *Science*, *258*, 640-643, 1992b.

Harmon, J.K., M.A. Slade, and R.S. Hudson, Mars Radar Scattering - Arecibo Goldstone Results at 12.6-cm and 3.5-cm Wavelengths, *Icarus*, *98* (2), 240-253, 1992a.

Harmon, J.K., M.A. Slade, and R.S. Hudson, Mars: Wavelength-Dependent Dual Polarization Global Scattering, in *Workshop on the Martian Surface and*

Atmosphere Through Time, edited by R.M. Haberle, et al., pp. 65-66, Lunar and Planetary Institute, 1992b.
Harmon, J.K., and M.A. Slade, An S-Band Radar Anomaly at the North Pole of Mercury, *Bulletin of the American Astronomical Society*, *23*, 1197, 1991.
Harmon, J.K., and M.A. Slade, S\X-Band Radar Observations of Mars at Arecibo and Goldstone During the 1988 Opposition, *EOS, Transactions, AGU, 70* (43), 1183, 1989.
Hudson, R. S., and S. J. Ostro. Recent radar modeling results: 1620 Geographos and 4179 Toutatis.*BAAS 29*, 966 (1997). [Abstract]
Hudson, R. S., and S. J. Ostro. Shape and non-principal axis spin state of asteroid 4179 Toutatis.*Science 270*, 84-86 (1995).
Hudson, R. S., and S. J. Ostro. Shape of asteroid 4769 Castalia (1989 PB) from inversion of radar images. *Science 263*, 940-943 (1994).
Hudson, R. S.. Three-dimensional reconstruction of asteroids from radar observations. *Remote Sensing Reviews 8*, 195-203 (1993).
Jurgens, R.F., F. Rojas, M.A. Slade, and A.F.C. Haldemann, Mercury: New Information on Topography and Orbital Elements, in *Lunar and Planetary Science XXIX*, Lunar and Planetary Institute, Houston (CD-ROM), 1998a.
Jurgens, R.F., F. Rojas, M.A. Slade, E.M. Standish, and J.F. Chandler, Mercury Radar Ranging Data from 1987 to 1997, *Astronomical Journal* (accep. 4/2/98), 1998b.
Jurgens, R.F., S.D. Howard, M.A. Slade, L. Robinett, and D. Strobert, A Preliminary Study of the Potential for High Resolution Parametric Radar Imaging of Mars by Ground Based Radar, in *Lunar and Planetary Science XXII*, pp. 671-672, LPI Publications Office, Houston, Texas, 1991.
Jurgens, R.F., C. Franck, W. Grenier, D. Howard, L. Robinett, M.A. Slade, and K. Wyss, Radar Observations of Tinatin Planitia: Goldstone 1988 Observations of Venus, in *Lunar and Planetary Science XXI*, Houston, Texas, 1990.
Koyama, Y., M. Yoshikawa, T. Iwata, J. Nakajima, M. Sekido, A. M. Nakamura, H. Hirabayashi, T. Okada, M. Abe, T. Nishibori, T. Nakamura, S. J. Ostro, D. K. Yeomans, D. Choate, R. A. Cormier, R. Winkler, R. F. Jurgens, J. D. Giorgini and M. A. Slade. Radar observations of an asteroid 1991JX. *Proceedings for the 28th ISAS Lunar and Planetary Symposium*, ISAS, Japan, pp. 201-204 (1995).
Margot, J. L., D. B. Campbell, R. F. Jurgens, M. A. Slade, and N. J. Stacey, High Resolution Topographic Maps of the Lunar South Pole, Bulletin of the American Astronomical Society, 29, 986, 1997 (abstract only).
Margot, J. L., D. B. Campbell, R. F. Jurgens, M. A. Slade, and N. J. Stacey, The Topography of the Lunar Polar Regions from Earth-based Radar Interferometry, Lunar and Planetary Science XXIX, 1845-1846, 1998 (abstract only).
Mitchell, D.L., R.S. Hudson, S.J. Ostro, and K.D. Rosema, Shape of Asteroid 433-Eros from Inversion of Goldstone Radar Doppler Spectra, *Icarus*, *131* (1), 4-14, 1998.
Mitchell, D.L., S.J. Ostro, R.S. Hudson, K.D. Rosema, D.B. Campbell, R. Velez, J.F. Chandler, I.I. Shapiro, J.D. Giorgini, and D.K. Yeomans, Radar Observations of Asteroids 1-Ceres, 2-Pallas, and 4-Vestal, *Icarus*, *124* (1), 113-133, 1996.
Moore, H.J., T.C. O'Brien, R.F. Jurgens, M.A. Slade, and T.W. Thompson, Preliminary Comparison of 3.5 CM and 12.6 CM Wavelength Continuous Wave Observations of Mars, in *Lunar and Planetary Science XXII*, pp. 917-918, LPI Publications Office, Houston, Texas, 1991.
Moore, H.J., and T.W. Thompson, A Radar-Echo Model for Mars, *Proceedings of Lunar and Planetary Science*, *21*, 457-472, 1991.
Muhleman, D.O., A.W. Grossman, and B.J. Butler, Radar Investigation of Mars, Mercury, and Titan, *Annual Review of Earth and Planetary Sciences*, *23*, 337-374, 1995.
Muhleman, D.O., B.J. Butler, and M.A. Slade, Radar Imaging of the Ice Deposits on Mercury's Poles, in *Lunar and Planetary Science XXV*, pp. 951-952, Houston, Texas, 1994.

Muhleman, D.O., A.W. Grossman, M.A. Slade, and B.J. Butler, Titan's Radar Reflectivity and Rotation, *Bulletin of the American Astronomical Society*, *25*, 1099, 1993.

Muhleman, D.O., A.W. Grossman, M.A. Slade, and B.J. Butler, The Surface of Titan and Titan's Rotation: What is Radar Telling Us, *Bulletin of the American Astronomical Society*, *24*, 954-955, 1992.

Muhleman, D.O., B.J. Butler, A.W. Grossman, and M.A. Slade, Radar Images of Mars, *Science*, *253* (5027), 1508-1513, 1991.

Muhleman, D.O., A.W. Grossman, B.J. Butler, and M.A. Slade, Radar Reflectivity of Titan, *Science*, *248*, 975-980, 1990.

Muhleman, D.O., A.W. Grossman, B.J. Butler, and M.A. Slade, Radar Echoes from the Surface of Titan, *EOS, Transactions, AGU*, *70* (43), 1182, 1989.

O'Brien, T.C., R.F. Jurgens, M.A. Slade, S.D. Howard, H.J. Moore, and T.W. Thompson, Observations of Mars During the 1990 Opposition from the Goldstone Solar System Radar Facility at 3.53 cm Wavelength, in *Lunar and Planetary Science XXII*, pp. 993-994, LPI Publications Office, Houston, Texas, 1991.

Ostro, S.J., L.A.M. Benner, D. Choate, C.R. Franck, R. Frye, J.D. Giorgini, S.D. Howard, R.F. Jurgens, D. Kelley, D.L. Mitchell, R. Rose, K.D. Rosema, M.A. Slade, R. Winkler, D.K. Yeomans, and R.S. Hudson, Near-Earth-Object Radar Astronomy at Goldstone in 1996, *28th DPS Meeting, Bulletin of the American Astronomical Society*, *28*, 971, 1996a.

Ostro, S.J., R.F. Jurgens, K.D. Rosema, R.S. Hudson, J.D. Giorgini, R. Winkler, D.K. Yeomans, D. Choate, R. Rose, M.A. Slade, S.D. Howard, D.J. Scheeres, and D.L. Mitchell, Radar Observations of Asteroid 1620 Geographos, *Icarus*, *121* (1), 46-66, 1996b.

Ostro, J.J., D. Choate, P. Dendrenos, C.R. Franck, J. Giorgini, D.L. Hills, D. Howard, R.F. Jurgens, M.S. Keesey, D.L. Mitchell, R. Rose, K.D. Rosema, M.A. Slade, D.R. Strobert, R. Winkler, and D.K. Yeomans, Asteroid 1991 JX: The 1995 Goldstone Radar Experiment, *27th DPS Meeting, Bulletin of the American Astronomical Society*, *27*, 687, 1995a.

Ostro, J.J., K.D. Rosema, R.S. Hudson, R.F. Jurgens, J.D. Giorgini, R. Winkler, D.K. Yeomans, D. Choate, R. Rose, M.A. Slade, S.D. Howard, and D.L. Mitchell, Extreme elongation of asteroid 1620 Geographos from radar images, *Nature*, *375*, 474-477, 1995b.

Ostro, S.J., K.D. Rosema, R.S. Hudson, J.D. Giorgini, R.F. Jurgens, R. Winkler, D.K. Yeomans, M.A. Slade, D. Howard, R. Rose, D.B. Campbell, P. Perillat, J.F. Chandler, and I.I. Shapiro, Asteroid 4179 Toutatis: First Results of the 1992 Radar Imaging Experiment, *Science*, *270*, 80-83, 1995c.

Ostro, J.J., D. Choate, P. Dendrenos, C.R. Franck, J. Giorgini, D.L. Hills, D. Howard, R.F. Jurgens, M.S. Keesey, D.L. Mitchell, R. Rose, K.D. Rosema, M.A. Slade, D.R. Strobert, R. Winkler, and D.K. Yeomans, Asteroid Radar Astronomy at Goldstone in the 1990s, *26th DPS Meeting, Bulletin of the American Astonomical Society*, *26*, 1165-1166, 1994.

Ostro, S.J., Planetary Radar Astronomy, *Reviews of Modern Physics*, *65*, (4), 1235-1279, 1993.

Ostro, S.J., R.F. Jurgens, K.D. Rosema, R. Winkler, D. Howard, R. Rose, M.A. Slade, D.K. Yeomans, D.B. Campbell, P. Perillat, J.F. Chandler, I.I. Shapiro, R.S. Hudson, P. Palmer, and I. de Pater, Radar Imaging of Asteroid 4179 Toutatis, *Bulletin of the American Astronomical Society*, *25*, 1126, 1993.

Ostro, S.J., D.B. Campbell, R.A. Simpson, R.S. Hudson, J.F. Chandler, K.D. Rosema, I.I. Shapiro, E.M. Standish, R. Winkler, D.K. Yeomans, R. Velez, and R.M. Goldstein, Europa, Ganymede, and Callisto - New Radar Results from Arecibo and Goldstone, *Journal of Geophysical Research Planets*, *97* (E11), 18227-18244, 1992.

Ostro, S.J., D.B. Campbell, J.F. Chandler, I.I. Shapiro, A.A. Hine, R. Velez, R.F. Jurgens, K.D. Rosema, R. Winkler, and D.K. Yeomans, Asteroid Radar Astrometry, *Astronomical Journal*, *102* (4), 1490-1502, 1991.

Ostro, S. J., K. D. Rosema, and R. F. Jurgens. The shape of Eros. *Icarus 84*, 334-351 1990).

Plaut, J.J., and R.E. Arvidson, Comparison of Goldstone and Magellan Radar Data in the Equatorial Plains of Venus, *Journal of Geophysical Research Planets*, *97* (E10), 16279-16291, 1992.

Plaut, J.J., R.E. Arvidson, and R.F. Jurgens, Radar Characteristics of the Equatorial Plains of Venus from Goldstone Observations - Implications for Interpretation of Magellan Data, *Geophysical Research Letters*, *17* (9), 1357-1360, 1990.

Roth, L.E., Schroeter Ratios for Martian Craters - Radar Results, *Earth Moon and Planets*, *52* (1), 27-49, 1991.

Senske, D.A., Geology of the Venus Equatorial Region from Pioneer Venus Radar Imaging, *Earth Moon and Planets*, *50-1* (JUL-), 305-327, 1990.

Simpson, R.A., J.K. Harmon, S.H. Zisk, T.W. Thompson, and D.O. Muhleman, Radar Determination of Mars Surface Properties, in *Mars*, edited by H.H. Kieffer, B.M. Jakosky, C.W. Snyder, and M.S. Matthews, pp. 652-685, University of Arizona Press, Tucson, 1992.

Slade, M.A., B.J. Butler, J.K. Harmon, R.F. Jurgens, and A.F.C. Haldemann, Radar Full-Disk Imaging and Topography of Mars During the 1999 Opposition, in *Lunar and Planetary Science XXIX*, Lunar and Planetary Institute, Houston (CD-ROM), 1998.

Slade, M.A., Goldstone Radar Observations of the 1999 Mars Opposition and other Observing Opportunities, *29th DPS Meeting, Bulletin of the American Astronomical Society*, *29*, 971, 1997.

Slade, M.A., R.F. Jurgens, F. Rojas, and A.F.C. Haldemann, New Radar Topography of Mercury and the Need for a Mercury DTM, in *28th Lunar and Planetary Science Conference*, pp. 1333-1334, Lunar and Planetary Institute, Houston, TX, Houston, TX, 1997.

Slade, M.A., R.F. Jurgens, and A.F.C. Haldemann, Radar Imaging and Topography of Ares/Maja Valles, Isidis, and Tritonis Lacus Pathfinder Landing Sites, in *27th Lunar and Planetary Science Conference*, pp. 1213-1214, Lunar and Planetary Institute, Houston, TX, Houston, TX, 1996.

Slade, M.A., R.F. Jurgens, A.F.C. Haldemann, and D.L. Mitchell, Hazard Evaluation for the Mars Pathfinder Prime Landing Site from Synthesis of Radar Ranging and Continuous Wave Observations During the 1995 Mars Opposition, *27th DPS Meeting, Bulletin of the American Astronomical Society*, *27* (3), 1103, 1995.

Slade, M.A., and R.F. Jurgens, Goldstone Radar Contributions to Mars Pathfinder Landing Safety, in *Mars Pathfinder Landing Site Workshop*, edited by M.P. Golombek, pp. 40, Lunar and Planetary Institute, 1994a.

Slade, M.A., and R.F. Jurgens, Goldstone Radar Observations of the 1995 Mars Opposition, *26th DPS Meeting, Bulletin of the American Astronomical Society*, *26*, 1114, 1994b.

Slade, M.A., R.F. Jurgens, J.D. Anderson, E.L. Lau, E.M. Standish, J.K. Harmon, D.B. Campbell, J.F. Chandler, and S.I. I., Radar Mapping and Precision Ranging of Mercury and Mars, in *XXIInd IAU General Assembly - Special Session on Solar System Radar Observations*, Den Haag, Netherlands, 1994c.

Slade, M.A., R.F. Jurgens, J.D. Anderson, E.L. Lau, J.K. Harmon, D.B. Campbell, J.F. Chandler, and S.I. I., The Equatorial Topography and the Orbit of Mercury from Goldstone and Arecibo Radar Ranging, *25th DPS Meeting, Bulletin of the American Astronomical Society*, *25*, 1090, 1993.

Slade, M.A., B.J. Butler, and D.O. Muhleman, Mercury Radar Imaging: Evidence for Polar Ice, *Science*, *258*, 635-640, 1992a.

Slade, M.A., B.J. Butler, and D.O. Muhleman, Mercury VLA Radar: A New Look at an

End-Member Planet, *24th DPS Meeting, Bulletin of the American Astronomical Society*, *24*, 956-957, 1992b.
Slade, M.A., B.J. Butler, and D.O. Muhleman, Mercury Goldstone/VLA Radar: Part I, *23rd DPS Meeting, Bulletin of the American Astronomical Society*, *23*, 1197, 1991a.
Slade, M.A., R.S. Hudson, T.C. O'Brien, and R.F. Jurgens, Mars Radar Reflectivity Images from 1988 and 1990 CW Spectra, in *Lunar and Planetary Science XXII*, Lunar and Planetary Institute, 1991b.
Slade, M.A., S. Zohar, and R.F. Jurgens, Venus: Improved Spin Vector from Goldstone Radar Observations, *Astronomical Journal*, *100* (4), 1369-1374 (plates 1396-1401), 1990.
Slade, M.A., J.K. Harmon, S.J. Ostro, R.F. Jurgens, and R. Zaveri, Mars South Residual Cap Observed in CW Radar Data, *EOS, Transactions, AGU, 70* (43), 1182, 1989.
Slade, M.A., S. Zohar, and R.F. Jurgens, Venus Spin Vector: 1980-82 Goldstone Radar Additions, in *19th Lunar and Planetary Science Conference*, LPI Publications Office, Houston, TX, 1988a.
Slade, M.A., R.F. Jurgens, and S.J. Ostro, Goldstone Solar System Radar, *20th DPS Meeting, Bulletin of the American Astronomical Society*, *20*, 678, 1988b.
Slade, M.A., S. Zohar, and R.F. Jurgens, Venus: Improved Spin Vector from Goldstone Radar Observations, in *18th Lunar and Planetary Science Conference*, LPI Publications Office, Houston, TX, 1987.
Thompson, T.W., T.C. O'Brien, R.F. Jurgens, M.A. Slade, and H.J. Moore, Mars Quasi-Specular Echoes: Preliminary Results at 3.5-cm Wavelength, in *Lunar and Planetary Science XXIII*, pp. 1431-1432, Houston, Texas, 1992.
Tryka, K.A., D.O. Muhleman, B.J. Butler, G. Berge, M.A. Slade, and A.W. Grossman, Correlation of Multiple Reflections from the Venus Surface with Topography, in *Lunar and Planetary Science XXII*, pp. 1417-1418, LPI Publications Office, Houston, Texas, 1991.
Yeomans, D. K., S. J. Ostro, and P. W. Chodas. Radar astrometry of near-Earth asteroids. *Astron. J. 94,* 189-200 (1987).
Zaitsev, A.L., S.J. Ostro, S.P. Ignatov, D.K. Yeomans, A.G. Petrenko, D. Choate, O.K. Margorin, R.A. Cormier, V.V. Mardyshkin, R. Winkler, O.N. Rghiga, R.F. Jurgens, V.A. Shubin, J.D. Giorgini, Krivtsov-AP, K.D. Rosema, Y.F. Koluka, M.A. Slade, A.L. Gavrik, V.B. Andreev, D.V. Ivanov, P.S. Peshin, Y. Koyama, M. Yoshikava, and A. Nakamura, Intercontinental Bistatic Radar Observations of 6489-Golevka (1991-JX), *Planetary and Space Science*, *45* (7), 771-778, 1997.
Zisk, S.H., P.J. Mouginis-Mark, J. Goldspiel, M.A. Slade, and R.F. Jurgens, Valley Systems on Tyrrhena Patera, Mars: Earth-Based Radar Measurements of Slopes, *Icarus*, *96*, 226-233, 1992.
Zisk, S.H., P.J. Mouginis-Mark, J. Goldspiel, M.A. Slade, and R.F. Jurgens, New Radar-Derived Topography for Tyrrhena Patera, Mars, in *Lunar and Planetary Science XXII*, pp. 1555-1556, LPI Publications Office, Houston, Texas, 1991.