A Data-Taking System for Planetary Radar Applications

Jean-Luc Margot[1,2]

[1]*Department of Earth, Planetary, & Space Sciences, UCLA, Los Angeles, CA 90095, USA, jlm@epss.ucla.edu*
[2]*Department of Physics & Astronomy, UCLA, Los Angeles, CA 90095, USA, jlm@astro.ucla.edu*

Most planetary radar applications require recording of complex voltages at sampling rates of up to 20 MHz. I describe the design and implementation of a sampling system that has been installed at the Arecibo Observatory, Goldstone Solar System Radar, and Green Bank Telescope. After many years of operation, these data-taking systems have enabled the acquisition of hundreds of data sets, many of which still await publication.

1. Motivation

Planetary radar astronomy is a discipline that enabled major advances in our understanding of the scale of the Solar System, spin states and surface properties of planets and satellites, and the physical and dynamical properties of asteroids (e.g., Ostro *et al.*, 2000; Giorgini *et al.*, 2002; Margot *et al.*, 2002; Chesley *et al.*, 2003; Campbell *et al.*, 2006; Ostro *et al.*, 2006; Margot *et al.*, 2007; Taylor *et al.*, 2007). For reviews of the field, see Ostro (1993); Campbell *et al.* (2002); Ostro *et al.* (2002); Benner *et al.* (2015). For an historical account of the development of the field up to 1996, see Butrica (1996).

The field is distinctive in part because essentially all results come from only two transmitting facilities, the Arecibo Planetary Radar and the Goldstone Solar System Radar. The facilities are complementary in that the former is ∼15 times more sensitive and the latter has access to a fraction of the sky that is ∼2.5 larger (Naidu *et al.*, 2016). The facilities also probe slightly different depths below the surface because Arecibo transmits primarily at S band (2380 MHz) whereas Goldstone transmits primarily at X band (8560 MHz). Bistatic observations with reception at the 100 m Green Bank Telescope (GBT) or other antennas also occur for a small fraction of the observations.

Most planetary radar observations yield either 1D power spectra or 2D range-Doppler images (Evans & Hagfors, 1968), although 3D topographic maps can be obtained in some circumstances (Margot *et al.*, 1999). The sampling rate requirements for power spectra are relatively modest (<60 kHz) because the Doppler broadening of Solar System bodies at S band and X band do not exceed 30 kHz, with the exception of Saturn's rings (Nicholson *et al.*, 2005). For 2D imaging, the transmitted waveforms are most commonly encoded with pseudo-noise (PN) binary phase codes or modulated with linear frequency (chirp) ramps (Margot, 2001). In both cases, the achievable range resolution is inversely proportional to the bandwidth of the transmitted waveform.

NASA funded a major upgrade of the Arecibo Observatory in the late 1990s, which included a 1 MW S-band transmitter that can support 25 MHz bandwidth modulation (Goldsmith, 1996). In practice, 7.5 m resolution images are obtained by encoding the transmitted waveform with a 0.05-μs-baud PN code, corresponding to a bandwidth of 20 MHz. However, the data acquisition systems available after the upgrade were limited to sampling rates of 5 MHz, a factor of four lower than required for maximum resolution. This

---

[1]Corresponding author.

situation prompted the development of a baseband recording system for use at Arecibo, GBT, and other receiving sites. This data-taking system was subsequently deployed at Goldstone as well.

2. Design Considerations

Radar echoes in two orthogonal polarizations are detected by low-noise receivers. The receiver signals are amplified, filtered, and typically converted to baseband prior to digitization for computer storage and processing. Important design considerations include the resolution of the analog-to-digital (A/D) converter and the number of bits that are retained for subsequent processing. The data rate is given by

$$d = 2 \times n_{\mathrm{pol}} \times n_{\mathrm{bits}} \times f_s, \tag{1}$$

where n_{pol} is the number of recorded polarizations, n_{bits} is the number of recorded bits, f_s is the sampling frequency in Hz, and the factor of 2 indicates that both the in-phase and quadrature components of the voltage signal are sampled, i.e., a complex quantity. For 8-bit sampling of 2 polarizations at 20 MHz, the data rate is 640 Mb/s or 80 MB/s, which was prohibitive after the Arecibo upgrade.

Fortunately, the first processing step in planetary radar imaging is a range compression operation implemented as a digital correlation. Hagen & Farley (1973) demonstrated that digital correlations can be carried out effectively with two-, three-, and four-level sampling of the input signals, resulting in surprisingly low degradation of the signal-to-noise ratio (SNR) compared to that obtained with a finely quantized signal. For instance, the ratio of the power obtained with a two-bit (four-level) sampler to the power obtained with an ideal correlator exceeds 88% for a wide range of quantizer threshold settings (Kogan, 1998). In particular, setting the sampling thresholds at zero and ± 0.996 times the standard deviation of the input voltage yields a correlator efficiency of 88.12% with integer output levels of {-3, -1, +1, +3} (Schwab, 1986). The design requirement was therefore established at 2-bit sampling of 2 polarizations at 20 MHz, or a data rate of 20 MB/s.

The requirements for continuous sampling at low bit resolution are unlike those of most scientific or industrial applications. Commercial data acquisition products typically prize sampling resolutions of at least 8 bits and provide no straightforward mechanism for retaining only the most significant bits. This realization led to a custom-built design and implementation for what became known as the Portable Fast Sampler (PFS), with available sampling modes listed in Table 1.

mode	channels	bits	sampling rate	data rate
0	2	1	(N/A)	
1	2	2	$5 - 40$ MHz	$2.5 - 20$ MB/s
2	2	4	$5 - 20$ MHz	$5 - 20$ MB/s
3	2	8	$5 - 10$ MHz	$10 - 20$ MB/s
4	4	1	(N/A)	
5	4	2	$5 - 20$ MHz	$5 - 20$ MB/s
6	4	4	$5 - 10$ MHz	$10 - 20$ MB/s
7	4	8	(N/A)	

Table 1.   Description of sampling modes.

3. Hardware Implementation

The sampling requirement is achieved with two Analog Devices AD9059/PCB, which are dual-channel 8-bit A/D boards with maximum conversion rates of 60 million samples per second. These boards require only a +5 V power supply and a TTL-compatible encode clock. Full-scale on the A/D converters is achieved for input signals of 1 V peak-to-peak driving a 50 Ω termination. Therefore, input voltages with standard deviations near 0.25 V (1 dBm) yield optimum two-bit sampling. Digital outputs are TTL compatible.

In order to emulate 2-, 4- or 8-bit sampling, the 32 A/D digital outputs are connected to a programmable logic device (PLD) for bit selection and packing. A device from the Altera MAX 7000S family (EPM7128SLC84-10) with plastic J-lead chip carrier (PLCC) 84-pin packaging is used for this purpose. It requires a +5 V power supply and accepts TTL-level input voltages. The supply voltages for internal logic and input buffers (VCCINT) and for output drivers (VCCIO) are both set to 5 V. The selected bits are packed into sixteen data bits that are sent to four differential line drivers (SN75ALS194) for RS-422 transmission over a 7-foot-long twisted pair cable (EDT CAB-AA 016-00427-00).

A parallel interface card (EDT PCI CD-20) is used to transfer the data to computer memory and storage disks at rates of up to 20 MB/s. The interface card is connected to the PCI bus of a rack-mounted computer that runs the Linux operating system. The interface card can handle four general-purpose control outputs (FUNCT0–3), which are used to specify the sampling mode (written to FUNCT1–3) and to toggle a data acquisition enable signal (written to FUNCT0).

Two station clock signals phase-locked to a high-accuracy frequency standard are required. The first signal is a one pulse-per-second (PPS) TTL signal, which is used to trigger the start of the data acquisition. The second signal is a +13 dBm ($\sim$3 Vpp into 50 Ohms) sampling clock of arbitrary frequency, although most observations are conducted with a 5, 10, or 20 MHz sampling clock. The sampling clock is a simple sine wave that is converted to a TTL square wave and distributed to the A/D boards and PLD.

The enclosure for the A/D boards, PLD, and associated electronics is a Lansing Instrument Corp. B2F18-001C, which is 2 rack units (3.47 in), full rack width (16.73 in), and 18 in deep. BNC connectors are used to connect the 1 PPS, sampling clock, and four analog input signals.

4. Software Implementation

A computer program (`pfs_radar`) written in C can be executed from the command line or graphical user interface to control the operation of the data-taking system. Command-line options enable specification of the sampling mode (`-m`), recording duration in seconds (`-secs`), and start time (`-start yyyy,mm,dd,hh,mm,ss`) specified in Universal Time. The computer clock is synchronized to accurate time servers with the Network Time Protocol (NTP).

Planetary radar observations require extreme (<10 ns) timing precision. Upon execution of the data-taking program, the computer allocates ring buffer memory, opens log and data files, then suspends execution until 0.5 s before the desired start time. At that point, the data acquisition enable bit (FUNCT0) is activated, which signals to the PLD that data acquisition will commence on the upcoming rising edge of the 1 PPS signal.

When the rising edge of the 1 PPS is detected while the data acquisition bit is enabled, the PLD toggles the Input Data Valid (IDV) bit, which instructs the 16-bit interface card to transfer data to PCI bus memory. The PLD is programmed to generate a Receive Timing (RXT) signal for use by the interface card, which stores inputs only at the rising edge of the RXT signal. Data are transferred 16 bits at a time until the C program detects that the end time of data-acquisition has been reached. At that point, the data acquisition bit is deactivated, ring buffers are cleared, the log file is flushed, and the whole process can start over.

Data files contain exclusively the raw data in packed format. Each data file name encodes the receiver start time in the format `datayyyymmddhhmmss`. Ancillary information about sampling mode, buffer sizes, data rates, etc. are stored in the separate ASCII log file. Data-taking progress can be monitored remotely by examining this log file.

Most radar observations proceed with multiple transmit/receive cycles, where the timing of the receive cycles can be calculated in advance. Many observations use a simple script that repeatedly invokes the data-taking program with the value of the next receive start time.

Ancillary programs enable data inspection and analysis in near real time. One can display histograms and statistics of the input data with `pfs_hist` and `pfs_stats`. Unpacking and downsampling of the data can be done with the programs `pfs_unpack` and `pfs_downsample`. Spectral analysis is facilitated with `pfs_fft`. The data-taking software and all ancillary programs are available on GitHub at https://github.com/UCLA-RADAR-Group/pfs.

5.   Applications

The data-acquisition system was installed at Arecibo (2 units), the Green Bank Telescope (2 units), and Goldstone (4 units). It has been used to acquire most of the radar echoes at Arecibo (2000–present), Goldstone (2001–2014), and Green Bank (2001–2017).

The system was used for the first radar detection of a Solar System object at NASA's Deep Space tracking station (DSS-63) in Madrid, Spain. The asteroid 6489 Golevka was detected on 4 June 1999 with the expected Doppler bandwidth and at the expected frequency. Observations of the same asteroid were also obtained at Arecibo in 2003 and led to the first detection of the Yarkovsky orbital drift (Chesley *et al.*, 2003).

Arecibo radar images of asteroid 1999 JM8 were obtained at 15 m resolution with the data-taking system on 1–9 August 1999. At the time, these images were the highest resolution images of an asteroid ever obtained (Figure 1). This distinction was lost when the NEAR-Shoemaker spacecraft lowered its orbit sufficiently close to asteroid 433 Eros. Analysis of the radar data revealed that the asteroid has an effective diameter of 7 km and a non-principal-axis rotation with a dominant periodicity near 7 days (Benner *et al.*, 2002).
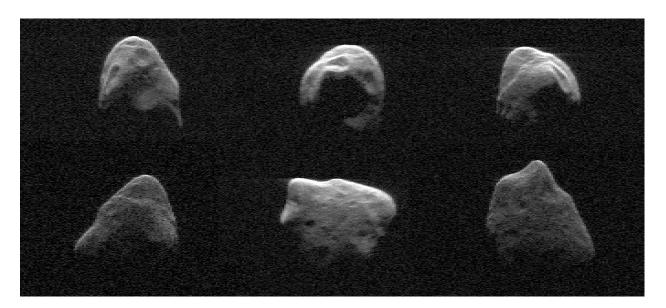

Fig. 1.   This sequence of 15 m resolution Arecibo radar images show asteroid 1999 JM8 on consecutive days.

Observations of the Moon with Arecibo transmitting at 2380 MHz and the 25 m VLBA antenna in St-Croix receiving were conducted on 19–21 November 2000. The data-taking system was used to record images at 30 m resolution (Figure 2).

The data-taking system enabled some of the first scientific observations at the Green Bank Telescope. Arecibo-GBT radar images of asteroid 2001 EC16 and Venus at 15 m and 150–300 m resolutions, respectively, were obtained on 24–26 March 2001. Because the round-trip light-time to the asteroid was 11 s, and because it takes several seconds to switch between transmit and receive modes, monostatic observations would have limited the frequency resolution to the reciprocal of the ~5 s receive time, approximately 0.2 Hz. Continuous transmission from Arecibo and continuous reception at the GBT for several minutes enabled the acquisition of spectra with two orders of magnitude better frequency resolution. One goal of the Venus observations was to obtain topographic maps with a 3D interferometric technique (Margot *et al.*, 2000).

Other notable radar observations from Arecibo include Saturn's rings in 2001, 2001, and 2003 (Nicholson *et al.*, 2005), binary asteroid 1999 KW4 at 7.5 m resolution in 2001 (Ostro *et al.*, 2006), and many observations of the Moon (e.g., Campbell *et al.*, 2007).

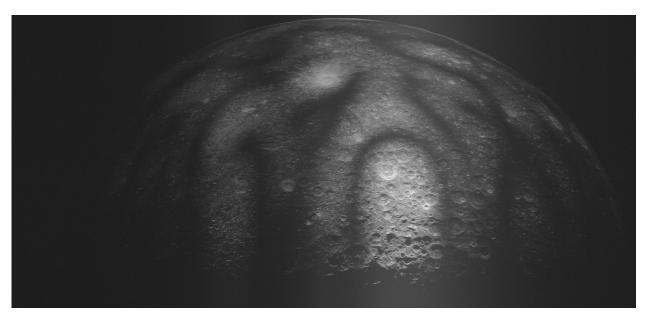The sampling system has been used in a Goldstone-GBT configuration to produce high-precision

Fig. 2. This Arecibo to St-Croix radar image shows the beam pattern of the Arecibo telescope painted on the surface of the Moon. The main lobe and first null are visible around the south polar region. Echoes from the rest of the Moon appear through the sidelobes of the beam pattern.

measurements of planetary spin states. The observations revealed that Mercury has a liquid outer core (Margot *et al.*, 2007) and enabled a measurement of the size of its core (Margot *et al.*, 2012). They also enabled the first measurement of the spin precession rate of Venus and revealed that Venus exhibits length-of-day variations of tens of minutes (Margot *et al.*, 2021).

Acknowledgments

References

Benner, L. A. M., Busch, M. W., Giorgini, J. D., Taylor, P. A. & Margot, J. L. [2015] "Radar Observations of Near-Earth and Main-Belt Asteroids," *Asteroids IV*, eds. Michel, P., DeMeo, F. E. & Bottke, W. F. (Univ. of Arizona Press), p. 165.

Benner, L. A. M., Ostro, S. J., Nolan, M. C., Margot, J. L., Giorgini, J. D., Hudson, R. S., Jurgens, R. F., Slade, M. A., Howell, E. S., Campbell, D. B. & Yeomans, D. K. [2002] *Meteoritics and Planetary Science* **37**, 779.

Butrica, A. J. [1996] *To See the Unseen*, NASA SP: 4218 (NASA).

Campbell, B. A., Campbell, D. B., Margot, J. L., Ghent, R. R., Nolan, M., Chandler, J., Carter, L. M. & Stacy, N. J. S. [2007] *IEEE Transactions on Geoscience and Remote Sensing* **45**, 4032, doi:10.1109/TGRS.2007.906582.

Campbell, D. B., Campbell, B. A., Carter, L. M., Margot, J.-L. & Stacy, N. J. S. [2006] *Nature* **443**, 835, doi:10.1038/nature05167.

Campbell, D. B., Hudson, R. S. & Margot, J. L. [2002] "Advances in planetary radar astronomy," *Review of Radio Science*, ed. W. Ross Stone (URSI).

Chesley, S. R., Ostro, S. J., Vokrouhlický, D., Čapek, D., Giorgini, J. D., Nolan, M. C., Margot, J. L., Hine, A. A., Benner, L. A. M. & Chamberlin, A. B. [2003] *Science* **302**, 1739, doi:10.1126/science.1091452.

Evans, J. V. & Hagfors, T. (eds.) [1968] *Radar Astronomy* (McGraw-Hill, New York).

Giorgini, J. D., Ostro, S. J., Benner, L. A. M., Chodas, P. W., Chesley, S. R., Hudson, R. S., Nolan, M. C., Klemola, A. R., Standish, E. M., Jurgens, R. F., Rose, R., Chamberlin, A. B., Yeomans, D. K. & Margot, J. L. [2002] *Science* **296**, 132, doi:10.1126/science.1068191.

Goldsmith, P. F. [1996] *IEEE Potentials* **15**, 38.

Hagen, J. B. & Farley, D. T. [1973] *Radio Science* **8**, 775, doi:10.1029/RS008i008p00775.

Kogan, L. [1998] *Radio Science* **33**, 1289, doi:10.1029/98RS02202.

Margot, J. L. [2001] "Planetary Radar Astronomy with Linear FM (chirp) Waveforms," Arecibo Technical and Operations Memo Series 2001-09, Arecibo Observatory, URL https://www.naic.edu/~astro/aotms/misc/chirp.pdf.

Margot, J. L., Campbell, D. B., Giorgini, J. D., Jao, J. S., Snedeker, L. G., Ghigo, F. D. & Bonsall, A. [2021] *submitted* .

Margot, J. L., Campbell, D. B., Jurgens, R. F. & Slade, M. A. [1999] *J. Geophys. Res.* **104**, 11875, doi:10.1029/1998JE900047.

Margot, J. L., Campbell, D. B., Jurgens, R. F. & Slade, M. A. [2000] *IEEE Trans. Geoscience and Remote Sensing* **38**, 1122, doi:10.1109/36.841991.

Margot, J. L., Nolan, M. C., Benner, L. A. M., Ostro, S. J., Jurgens, R. F., Giorgini, J. D., Slade, M. A. & Campbell, D. B. [2002] *Science* **296**, 1445, doi:10.1126/science.1072094.

Margot, J. L., Peale, S. J., Jurgens, R. F., Slade, M. A. & Holin, I. V. [2007] *Science* **316**, 710, doi:10.1126/science.1140514.

Margot, J. L., Peale, S. J., Solomon, S. C., Hauck, S. A., II, Ghigo, F. D., Jurgens, R. F., Yseboodt, M., Giorgini, J. D., Padovan, S. & Campbell, D. B. [2012] *Journal of Geophysical Research (Planets)* **117**, E00L09, doi:10.1029/2012JE004161.

Naidu, S. P., Benner, L. A. M., Margot, J. L., Busch, M. W. & Taylor, P. A. [2016] *Astron. J.* **152**, 99, doi:10.3847/0004-6256/152/4/99.

Nicholson, P. D., French, R. G., Campbell, D. B., Margot, J.-L., Nolan, M. C., Black, G. J. & Salo, H. J. [2005] *Icarus* **177**, 32, doi:10.1016/j.icarus.2005.03.023.

Ostro, S. J. [1993] *Rev. Modern Phys.* **65**, 1235, doi:10.1103/RevModPhys.65.1235.

Ostro, S. J., Hudson, R. S., Benner, L. A. M., Giorgini, J. D., Magri, C., Margot, J. L. & Nolan, M. C. [2002] "Asteroid radar astronomy," *Asteroids III*, eds. Bottke, W. F., Cellino, A., Paolicchi, P. & Binzel, R. P. (Univ. of Arizona Press), p. 151.

Ostro, S. J., Hudson, R. S., Nolan, M. C., Margot, J. L., Scheeres, D. J., Campbell, D. B., Magri, C., Giorgini, J. D. & Yeomans, D. K. [2000] *Science* **288**, 836, doi:10.1126/science.288.5467.836.

Ostro, S. J., Margot, J. L., Benner, L. A. M., Giorgini, J. D., Scheeres, D. J., Fahnestock, E. G., Broschart, S. B., Bellerose, J., Nolan, M. C., Magri, C., Pravec, P., Scheirich, P., Rose, R., Jurgens, R. F., De Jong, E. M. & Suzuki, S. [2006] *Science* **314**, 1276, doi:10.1126/science.1133622.

Schwab, F. [1986] "Two-bit correlators: Miscellaneous results," VLBA Correlator Memo 75, National Radio Astronomy Observatory.

Taylor, P. A., Margot, J. L., Vokrouhlický, D., Scheeres, D. J., Pravec, P., Lowry, S. C., Fitzsimmons, A., Nolan, M. C., Ostro, S. J., Benner, L. A. M., Giorgini, J. D. & Magri, C. [2007] *Science* **316**, 274, doi:10.1126/science.1139038.