Jet Propulsion Laboratory
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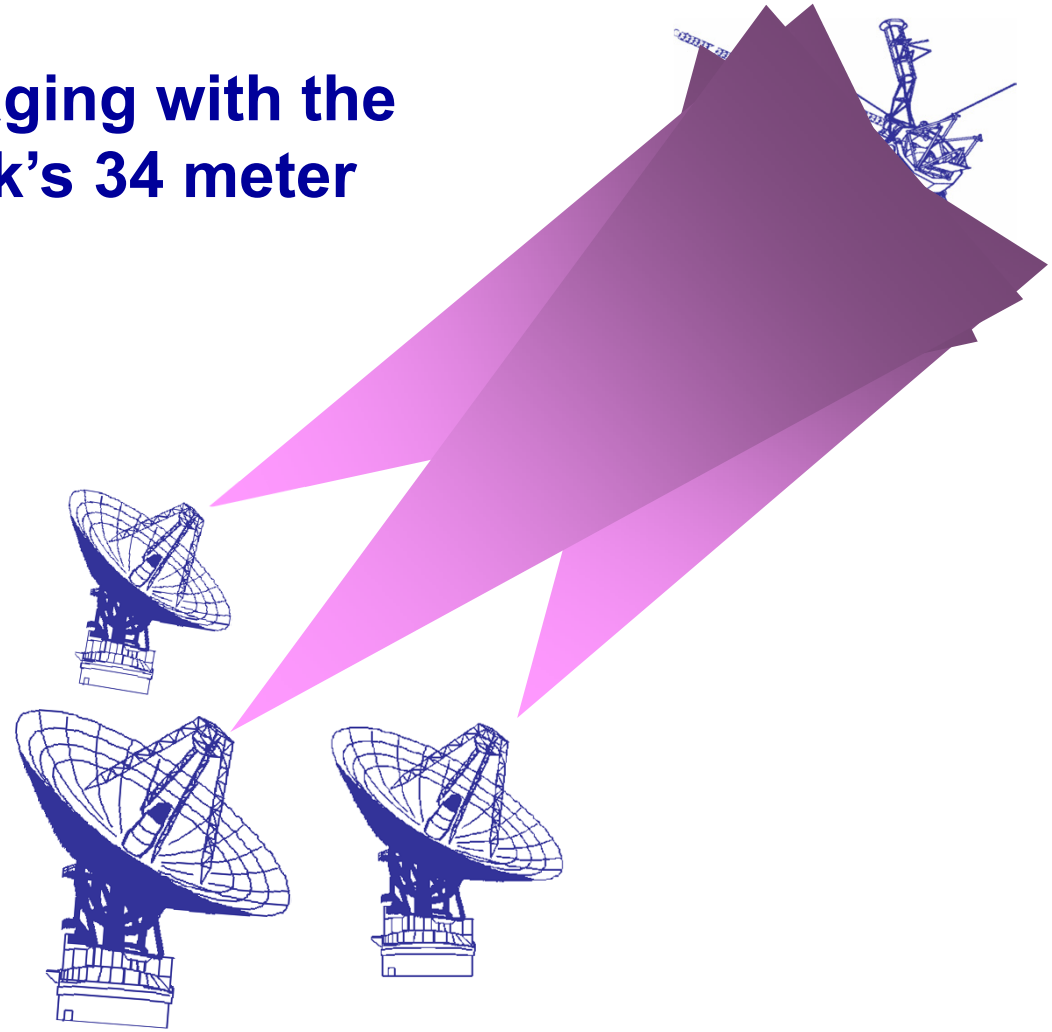
Planetary Radar Imaging with the Deep-Space Network's 34 meter Uplink Array



V. Vilnrotter, P. Tsao, D.Lee,
T. Cornish, J. Jao, M. Slade

March 11, 2011

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UPLINK ARRAYING TO DEEP-SPACE IS CURRENTLY BEING DEMONSTRATED AT JPL

- MOON-BOUNCE CALIBRATION, RE-POINTING, LONG-TERM PHASE CONTROL, AND CONTINUOUS TRACKING OF REAL DEEP-SPACE PROBES HAS BEEN DEMONSTRATED
- PLANETARY RADAR IMAGING IS CURRENTLY BEING INVESTIGATED

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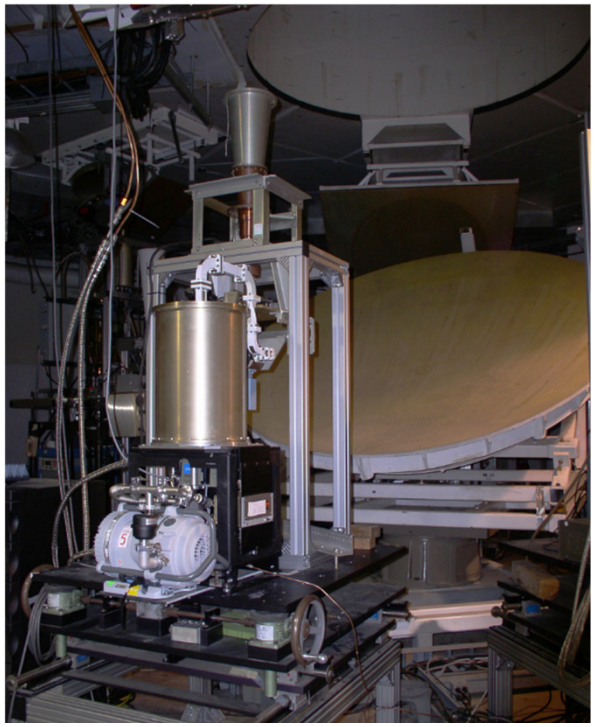
Picture of Apollo cluster, forming transmitter part of Uplink Array (DSS-24, DSS-25, DSS-26)

- Three 34m BWG antennas, 20 KW transmitters
- Array spans ~ 500 meters
  - Antenna null-to-null beamwidth ~ 170 mdegs
  - DSS-24 – DSS-25 baseline ~ 23 mdegs
  - DSS-24 – DSS-26 baseline ~ 15 mdegs

7.15 GHz Uplink Array receiver at the DSS-13 pedestal room

- Upgraded to cryogenic LNA
- X-band output to MMS
- 321.4 MHz IF to RSR (DSS-13)
- 460 MHz IF to GSSR (DSS-14)



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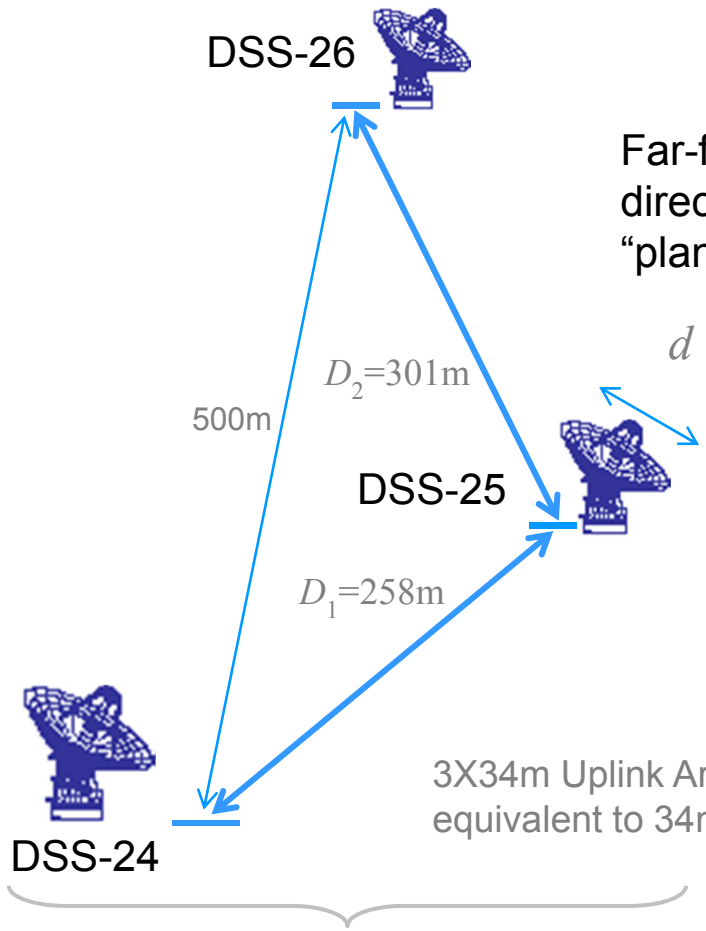
FAR-FIELD PATTERNS OF THE APOLLO CLUSTER

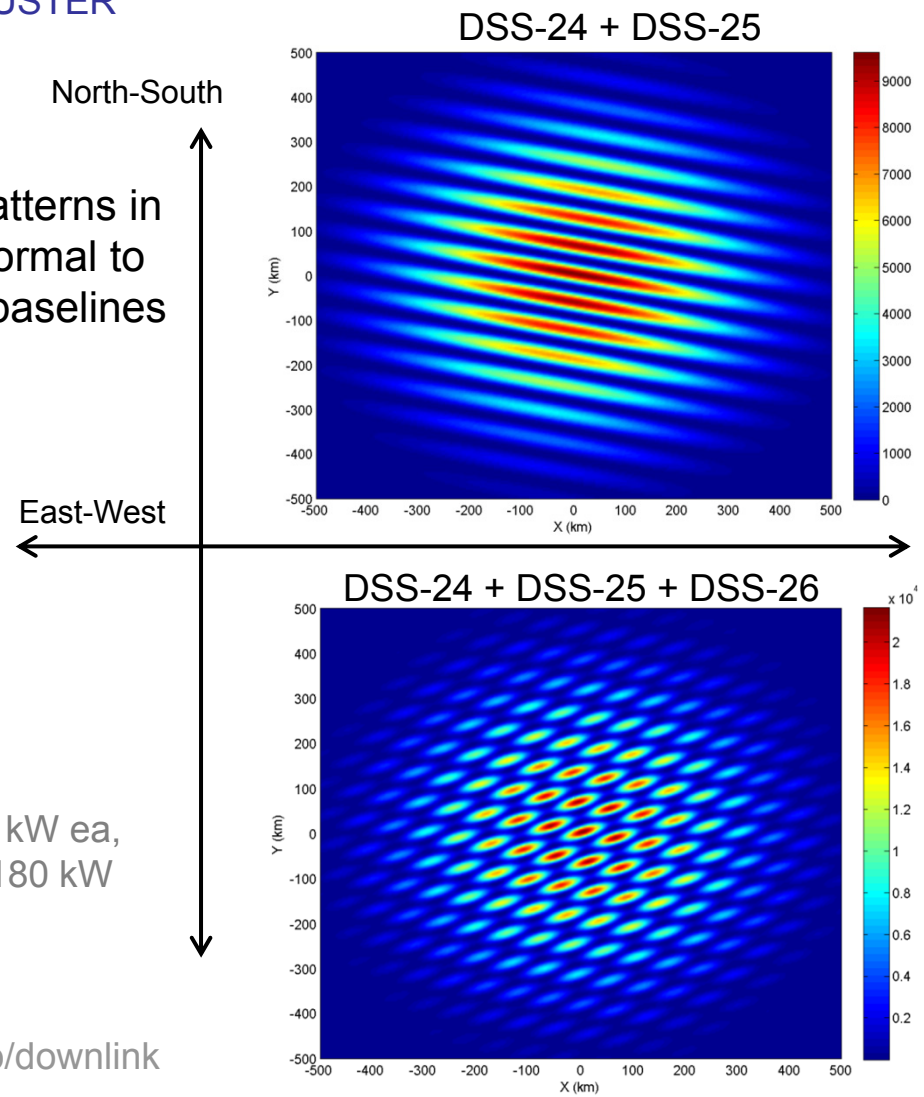


Far-field patterns in direction normal to "plane" of baselines

3X34m Uplink Array, 20 kW ea, equivalent to 34m with 180 kW

Uplink Array of 34m antennas

- Each element still available for single-antenna up/downlink



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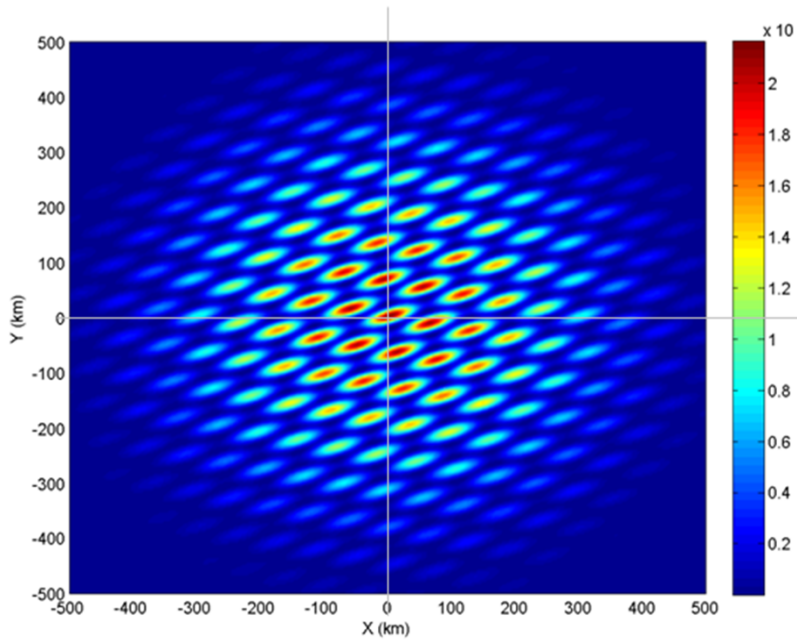
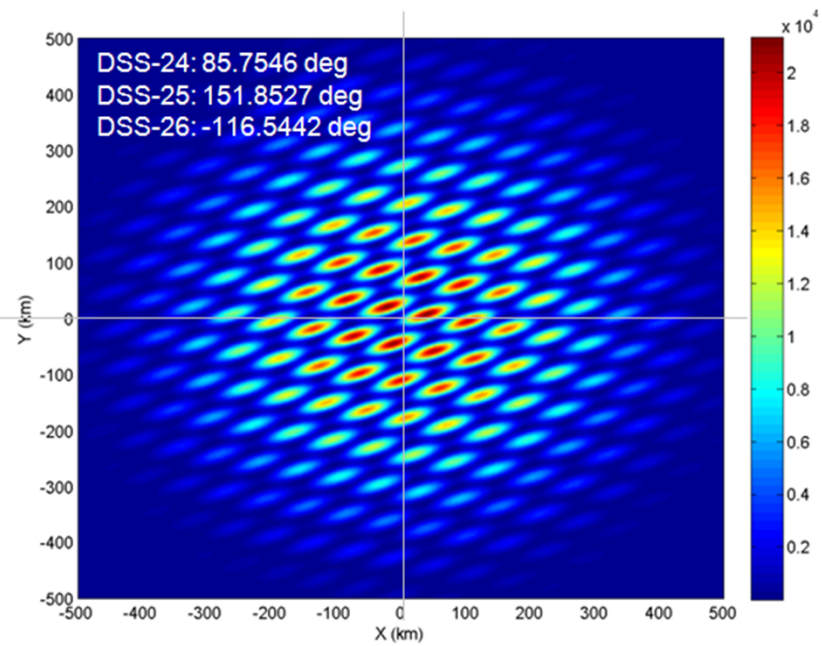
EFFECT OF RANDOM PHASE ON 3-ANTENNA ARRAY

With perfect phasing, peak of array far-field pattern maximized on-axis

With randomized phase, array far-field pattern retains basic structure, but array peak is shifted off desired direction





- Regular structure suggests simple extension of 2-antenna calibration approach:
  - obtain Doppler-delay image of target; estimate phase offsets for both independent baselines
- Efficient scanning of entire primary beam possible, using a few phase-shifts

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SPS frequency predicts for DSS-25: $f(t)$

Geometry-derived phase difference, $p(t)$:

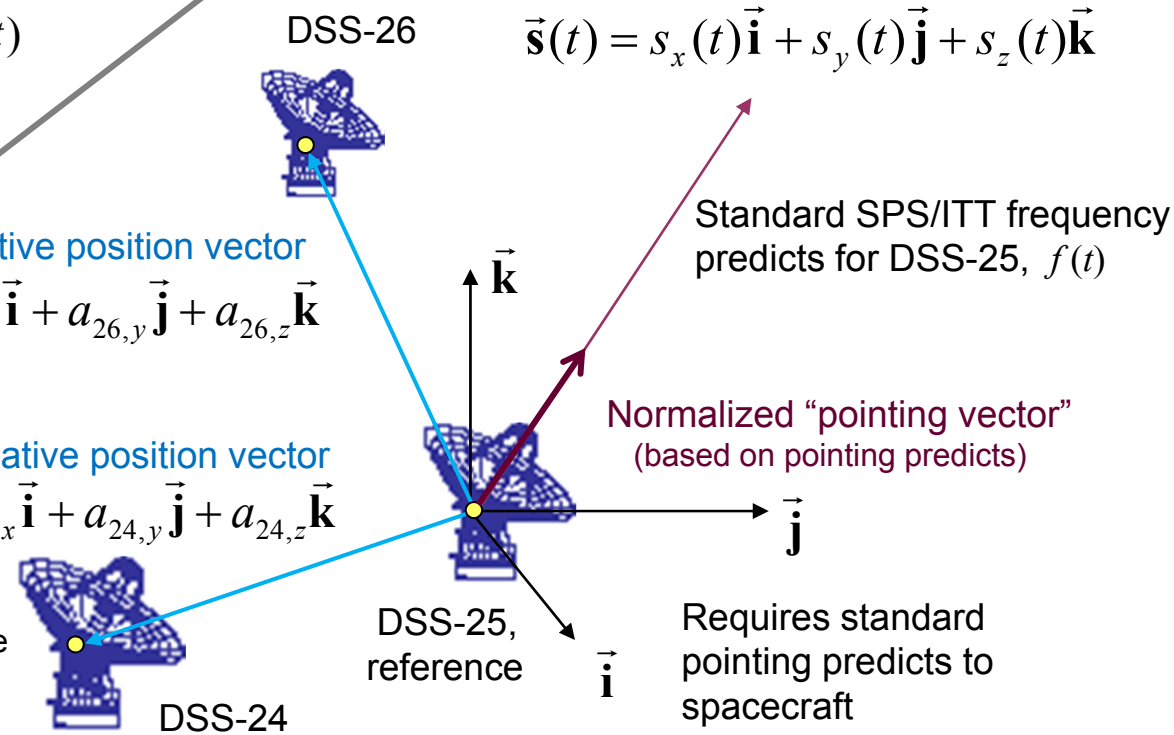
DSS *n*, $p_n(t) = \frac{2\pi}{\lambda}\vec{\mathbf{a}}_n \cdot \vec{\mathbf{s}}(t)$

Geometry-derived frequency difference, $f_\Delta(t)$:

DSS *n*, $f_{\Delta,n}(t) = \frac{2\pi}{\lambda}\vec{\mathbf{a}}_n \cdot \frac{\partial}{\partial t}\vec{\mathbf{s}}(t)$

$$f_n(t) = f(t) + f_{\Delta,n}(t)$$

Pointing-based frequency predicts derived from first principles to minimize differential phase error



- Precise knowledge of relative position vector coefficients is essential for accurate frequency and phase predicts
- Accurate coefficients were provided via previous VLBI solution for the DSS-24/25/26 phase centers (C. Jacobs, private communication)

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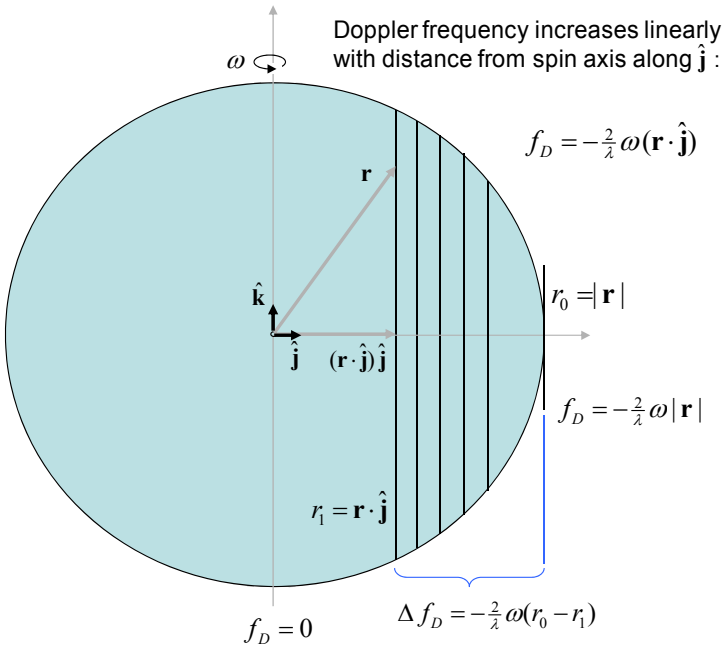
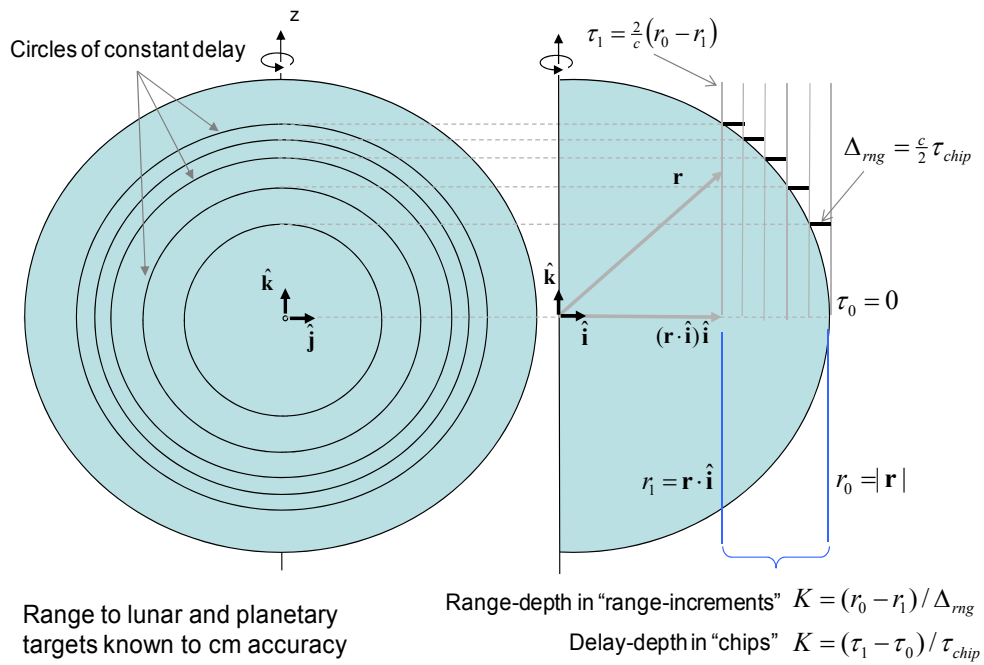
Rotating Sphere Model for Moon and Planets





Doppler frequency increases linearly from the center, generating constant frequency "Doppler slices" parallel to the apparent spin axis of a sphere.

Concentric circles of increasing delay from the closest point, the sub-radar point, with definition of "range-increments" and "delay-depth" on a sphere.

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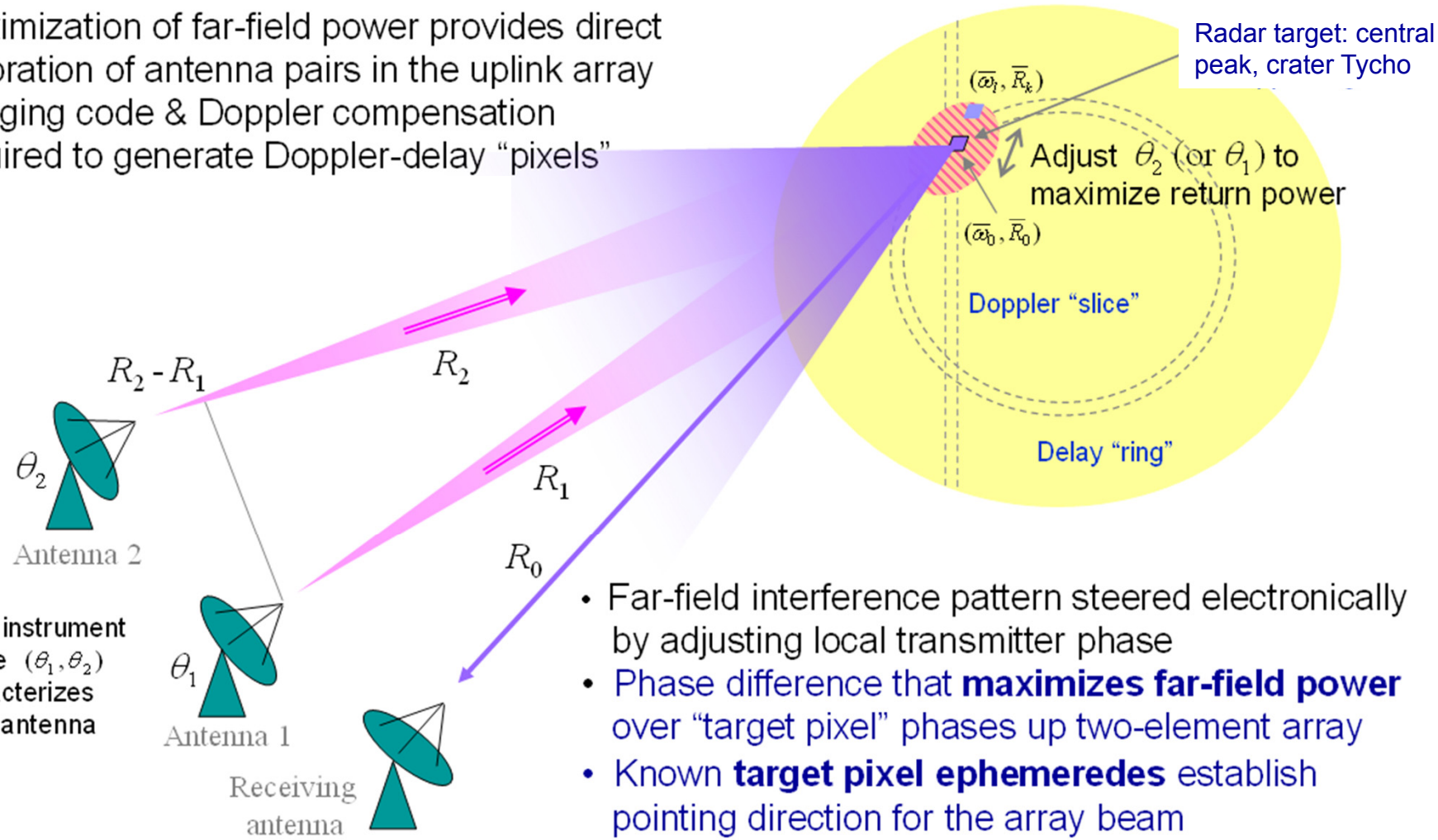
Transmit-Mode Uplink Array Calibration Technique: "Moon-Bounce"

- Maximization of far-field power provides direct calibration of antenna pairs in the uplink array
- Ranging code & Doppler compensation required to generate Doppler-delay "pixels"



- Far-field interference pattern steered electronically by adjusting local transmitter phase
- Phase difference that **maximizes far-field power** over "target pixel" phases up two-element array
- Known **target pixel ephemeredes** establish pointing direction for the array beam

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CW ECHO POWER, NOISE POWER, AND SNR ESTIMATES

$$P_r = \delta_r \sigma_r \eta_{rt} P_t \left(\frac{d_r}{2R}\right)^2 = \delta_r \sigma_r \eta_{rt} P_t \left(\frac{d_r}{R}\right)^2 \qquad \delta_r = \min[1, (d_t D / R)^2]$$

$$P_n = kT_{sys} B$$

$$SNR = \frac{P_r}{P_n} = \frac{\delta_r \sigma_r \eta_{rt} P_t}{kT_{sys} B}\left(\frac{d_r^2}{R^2}\right)$$

$k = 1.38 \times 10^{-23}$ $\qquad d_r = 34$

$P_t = 2 \times 10^4$ $\qquad \eta_{rt} = 0.5$

$\delta_r = 1$, $\sigma_r = 0.001$, $B = 30$ Hz and $T_{sys} = 100$ k $\qquad SNR_{Moon} \cong 1.7 \times 10^6 \quad (62\text{ dB})$

$\delta_r = 9 \times 10^{-4}$, $\sigma_r = 0.1$, $B = 300$ Hz and $T_{sys} = 36$ k $\qquad SNR_{Mercury} \cong 1 \quad (0\text{ dB})$

$\delta_r = 2.25 \times 10^{-2}$, $\sigma_r = 0.1/10$, $B = 100$ Hz, $T_{sys} = 36$ k $\qquad SNR \cong 30.8 \quad (14.9\text{ dB})$

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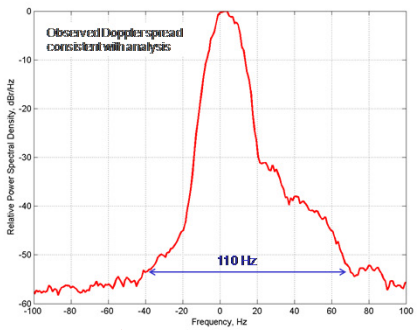
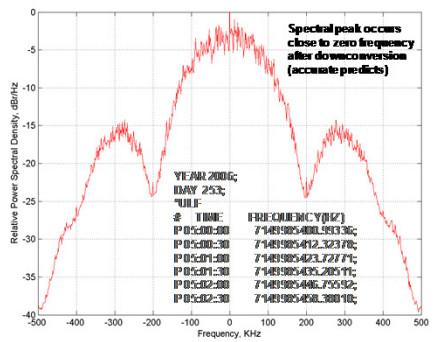
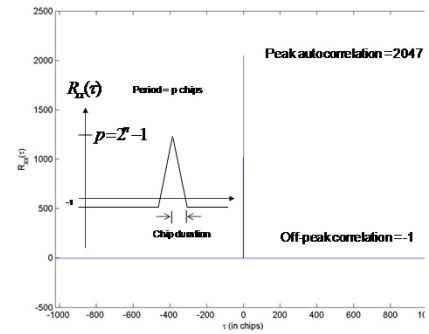
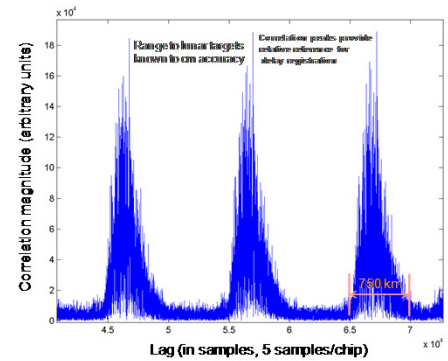




a) Doppler-broadened echo from the Tycho region;
b) Spectrum of received PN-modulated echo.

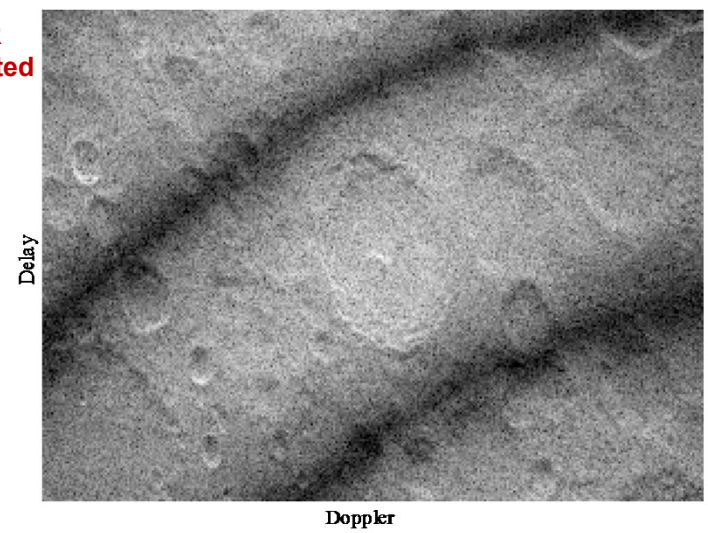


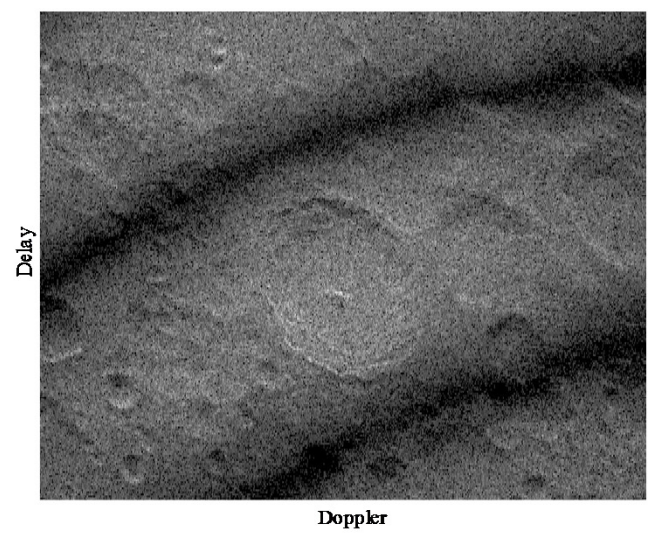


a) Simulated autocorrelation function of PN11 sequence ;
b) Correlation property of observed echo from Tycho region.

Measured SNR close to predicted 62 dB

GSSR receiver processing





RSR receiver processing

DSS-24/25 transmitting 25 kW, Uplink Array cryogenic receiver: a) GSSR and b) RSR processing, Tycho image comparison.

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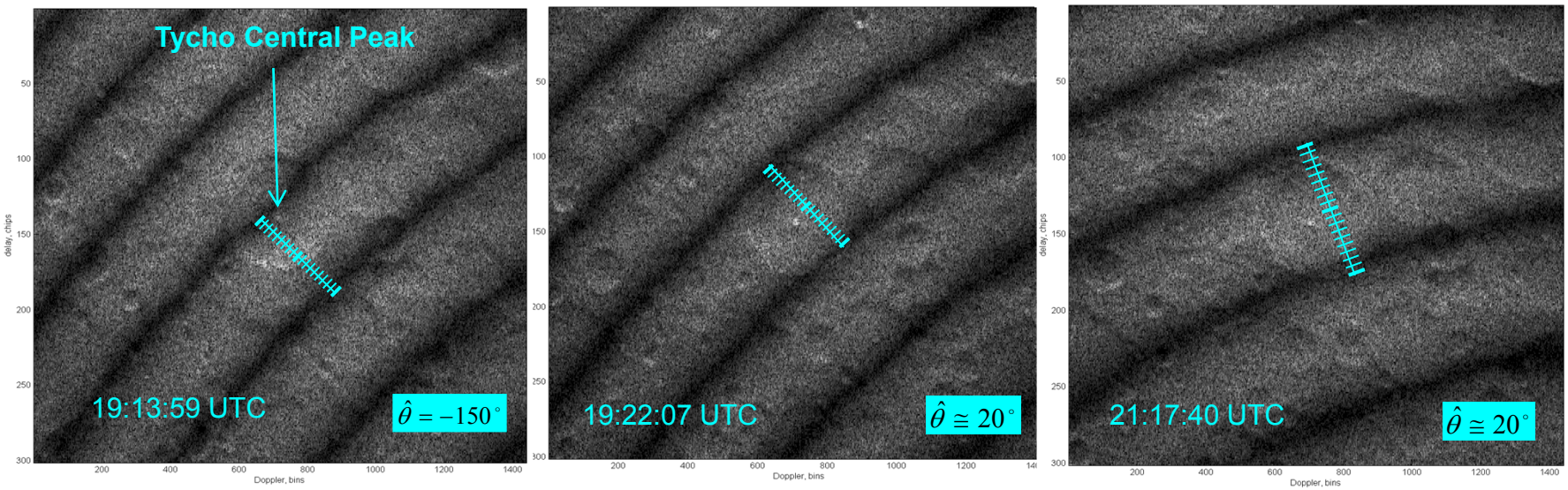
Two-Antenna Uplink Array Calibration + Far-Field Stability test (DOY-196)



- Uplink Array calibration target (Tycho CP) initially -150 electrical degrees from fringe peak
- After rough-calibration, single correction applied to DSS-24 carrier phase
  - Phase correction placed Uplink Array fringe peak within ~ 10 electrical degrees of lunar target
- Target remained within ~ 20 degrees of peak for about 2 hours (end-of-track)
  - Real-time phase corrections were applied to DSS-24 to mitigate ground-system phase drift

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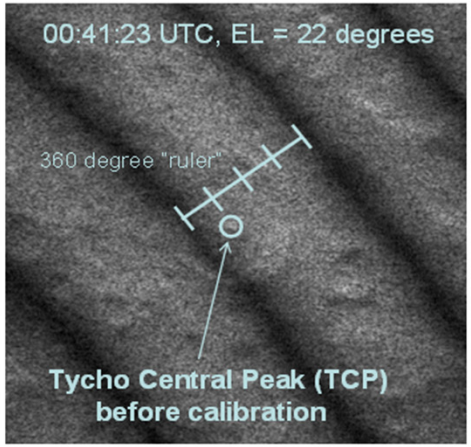
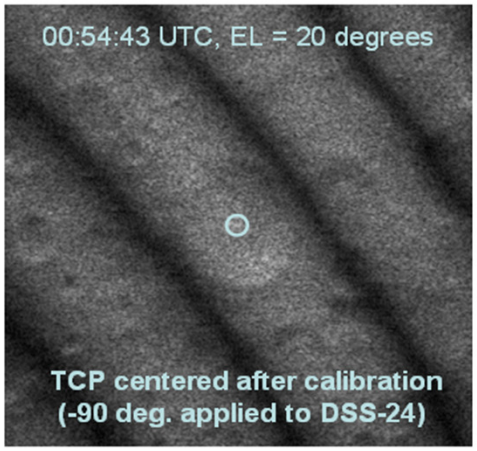
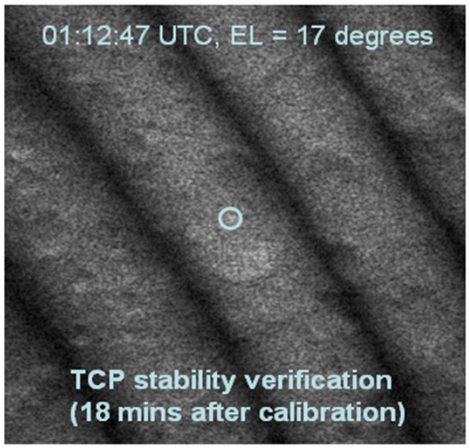
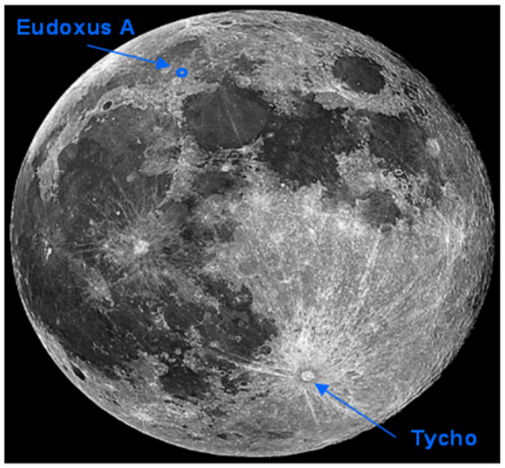
CALIBRATION-VECTOR TRANSLATION DEMO; DSS-24/25, DSS-13; DOY-257







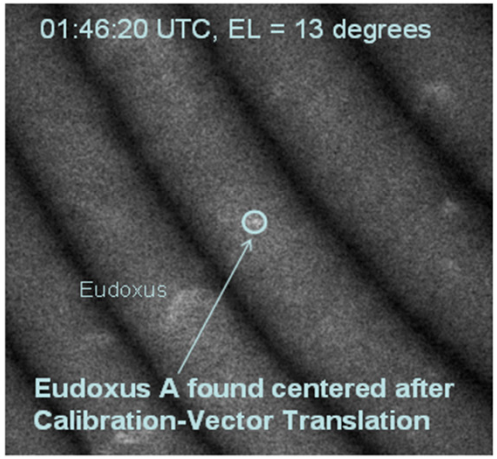
Top three Doppler-delay images: Standard calibration and stability verification via Tycho Central Peak



Optical image of full Moon, showing locations of calibration and vector-translation targets

Right: Demonstration of Calibration-Vector Translation concept via secondary target Eudoxus A, using computed phase and frequency predicts

Ground-phase was monitored at SPC-10, but no phase corrections were applied (phase difference remained within ± 5 degrees throughout the entire track)



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UPLINK ARRAY PLANETARY DOPPLER-DELAY IMAGING

- Radar echo power falls off as fourth power of distance: $P \propto R^{-4}$
- Mercury, Venus, and Mars can provide detectable echo power with 2-3 element Uplink Array and 34 meter receiver
- EIRP of 2-element 34m Uplink Array each with 20 kW transmitters equivalent to 70m antenna with 20 kW
- Detection of extremely weak planetary echoes requires very accurate frequency and range predicts
- First attempt to image Mercury with Uplink Array during May 1st, 2010 close approach
- First attempt to image Venus occurred on October 24th, 2010

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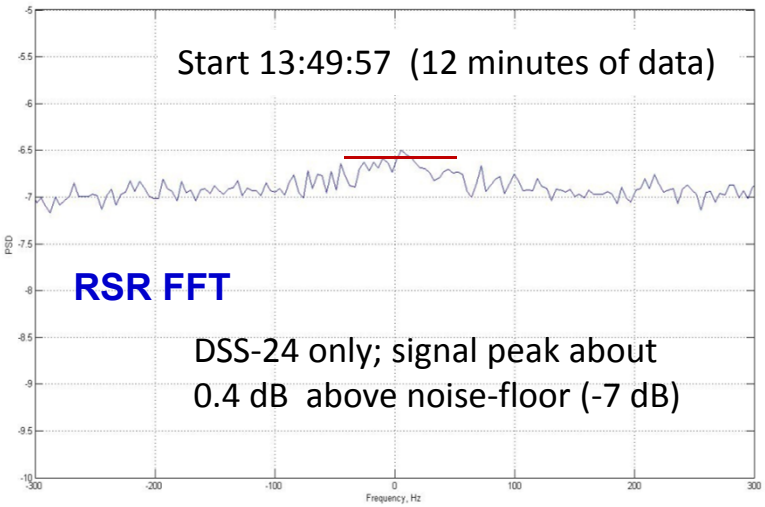
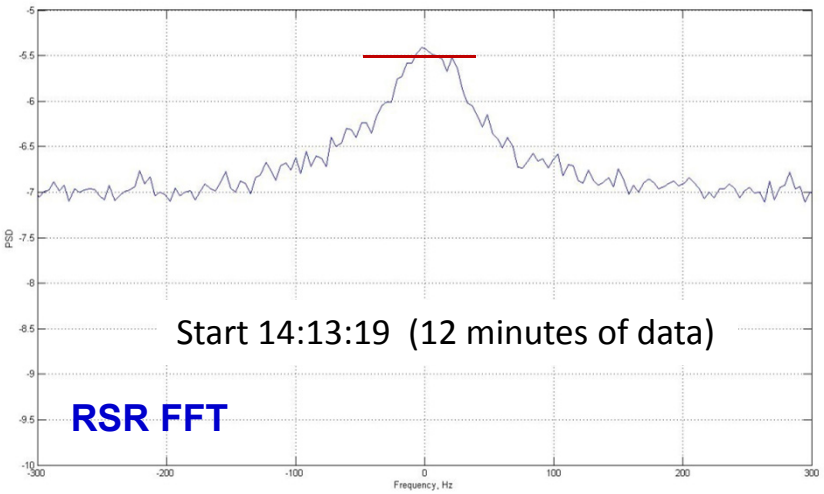
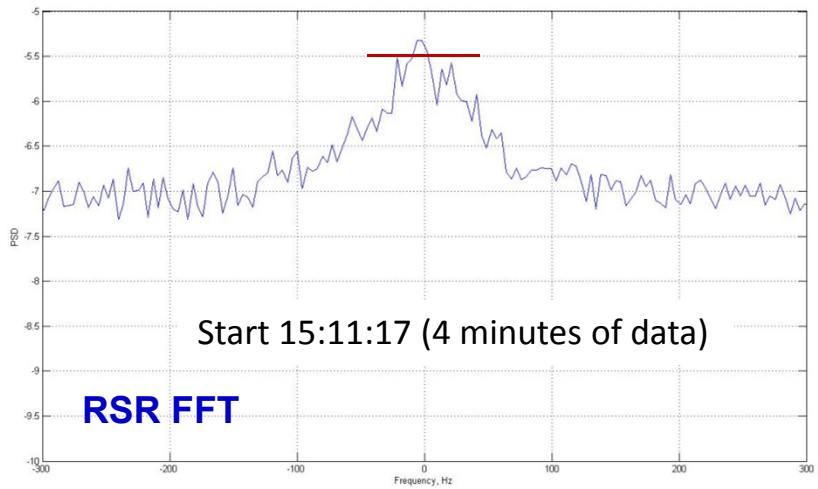


DSS-24/25 Phasing Experiment (DOY-121):

- DSS-24/25 transmitted 20 kW (carrier, PN11 code)
  - Array EIRP equivalent to 70m, transmitting 20 kW
- Successfully recorded DSS-24 carrier echo
  - Doppler-broadened carrier observed after 1 RTLT
  - RSR FFT: signal ~ 0.45 dB above noise-floor
- Successfully recorded DSS-24+DSS-25 carrier echo
  - RSR FFT: signal ~ 1.5 dB above noise-floor
  - Array combining gain: 3.7 (5.7 dB) over DSS-24
  - Array remained phased up throughout the track

DSS-24+DSS-25; signal peak about 1.5 dB above noise-floor





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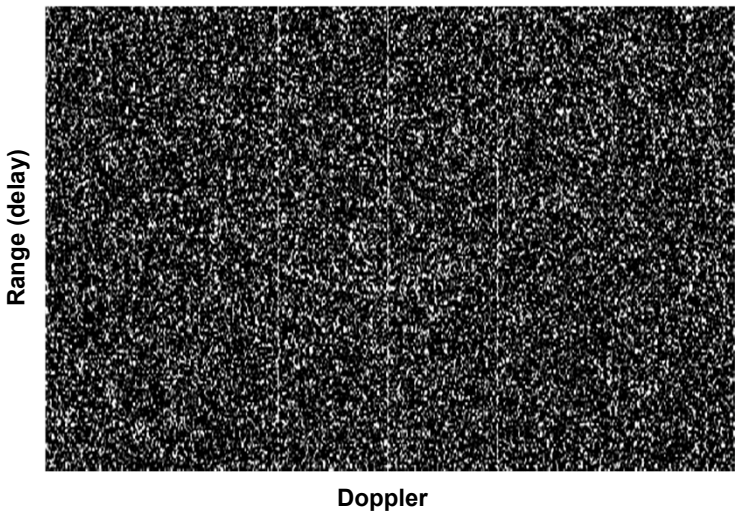
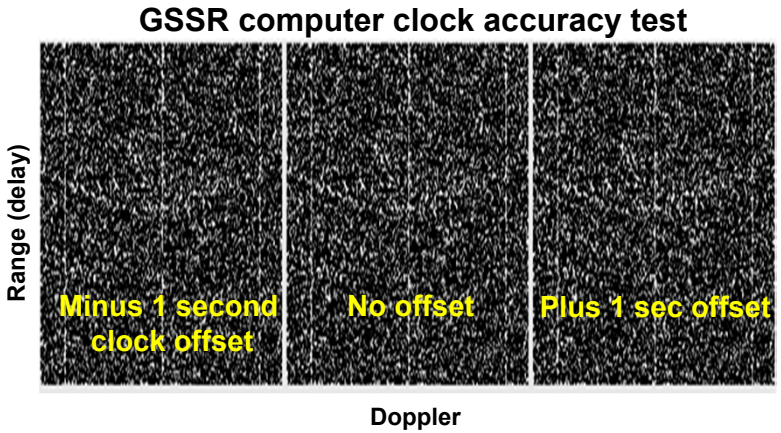
Mercury Imaging Experiment (DOY-121, 2010)

- Two 34m Apollo antennas, DSS-24/25, were phased up, transmitted 20 kW Doppler-compensated PN-modulated X-band carrier towards Mercury
- GSSR receiver at DSS-13 recorded faint Mercury signature



Original Mercury Doppler-delay image, obtained with GSSR receiver at DSS-13 on DOY-121, 1510-1550 UTC



Processed data to improve contrast, determine best computer clock setting, and extract image from data-files recorded after 1600 UTC with RSR and GSSR receivers

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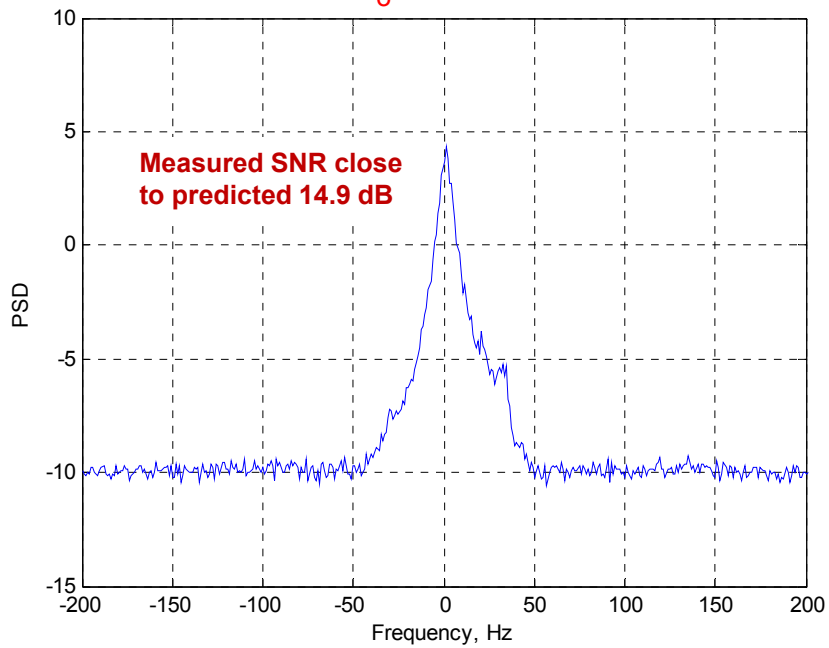
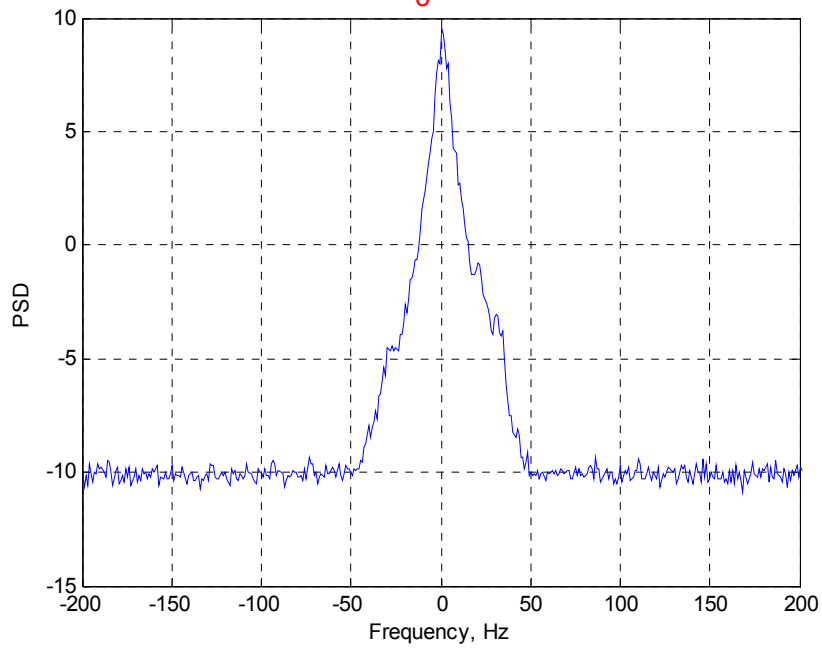
CW ECHOS FROM VENUS, DOY-294, RSR RECEIVER (DSS-13)

DSS25 Single Antenna CW FFT
C/N_o ~ 14 dB



DSS24+25 Two Antenna CW FFT
C/N_o ~ 20 dB



Venus echo for single and two-antenna Uplink Array illumination with RSR processing at DSS-13: SNR's of 14 and 20 dB as predicted, and demonstrating 6 dB array gain for the two-antenna array.

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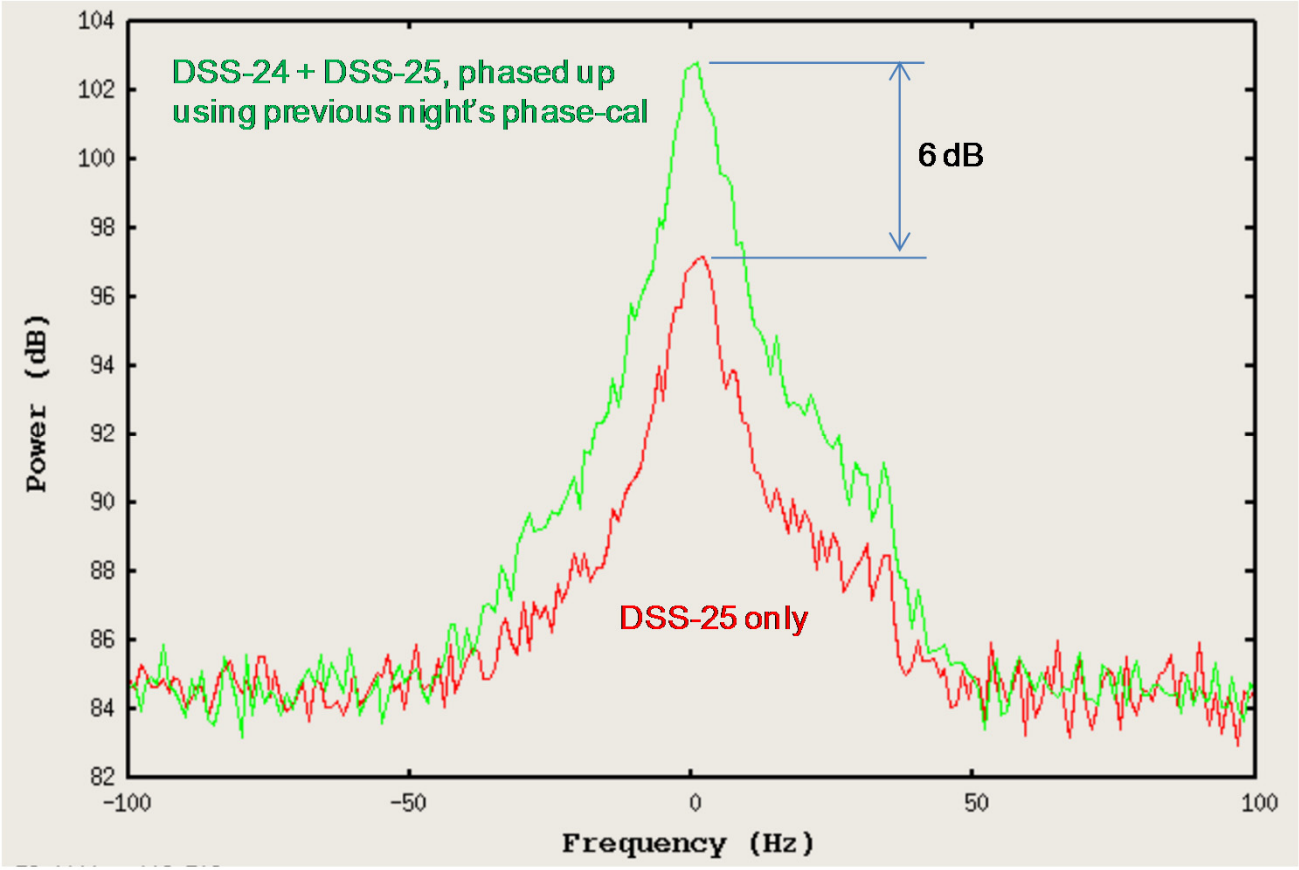

Venus echo for single antenna and two-antenna Uplink Array illumination with GSSR processing, demonstrating 6 dB array gain for the two-antenna array.

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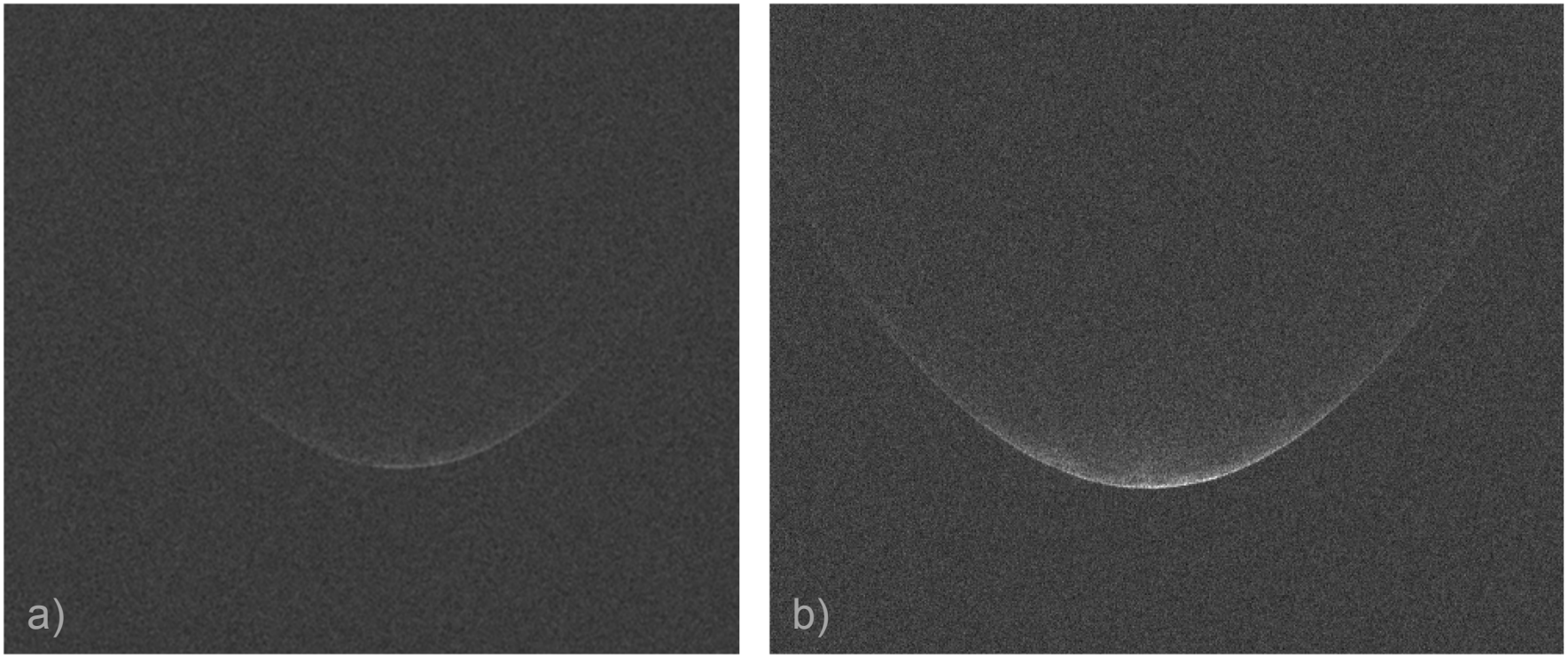

Doppler-delay images of Venus, taken on DOY-297, GSSR processing (4096 FFT): a) Single Antenna illumination (DSS-25); b) Two-antenna phased-array illumination (DSS-24 + DSS-25), showing greatly improved image quality.

Range increases along the vertical axis, Doppler along the horizontal axis.

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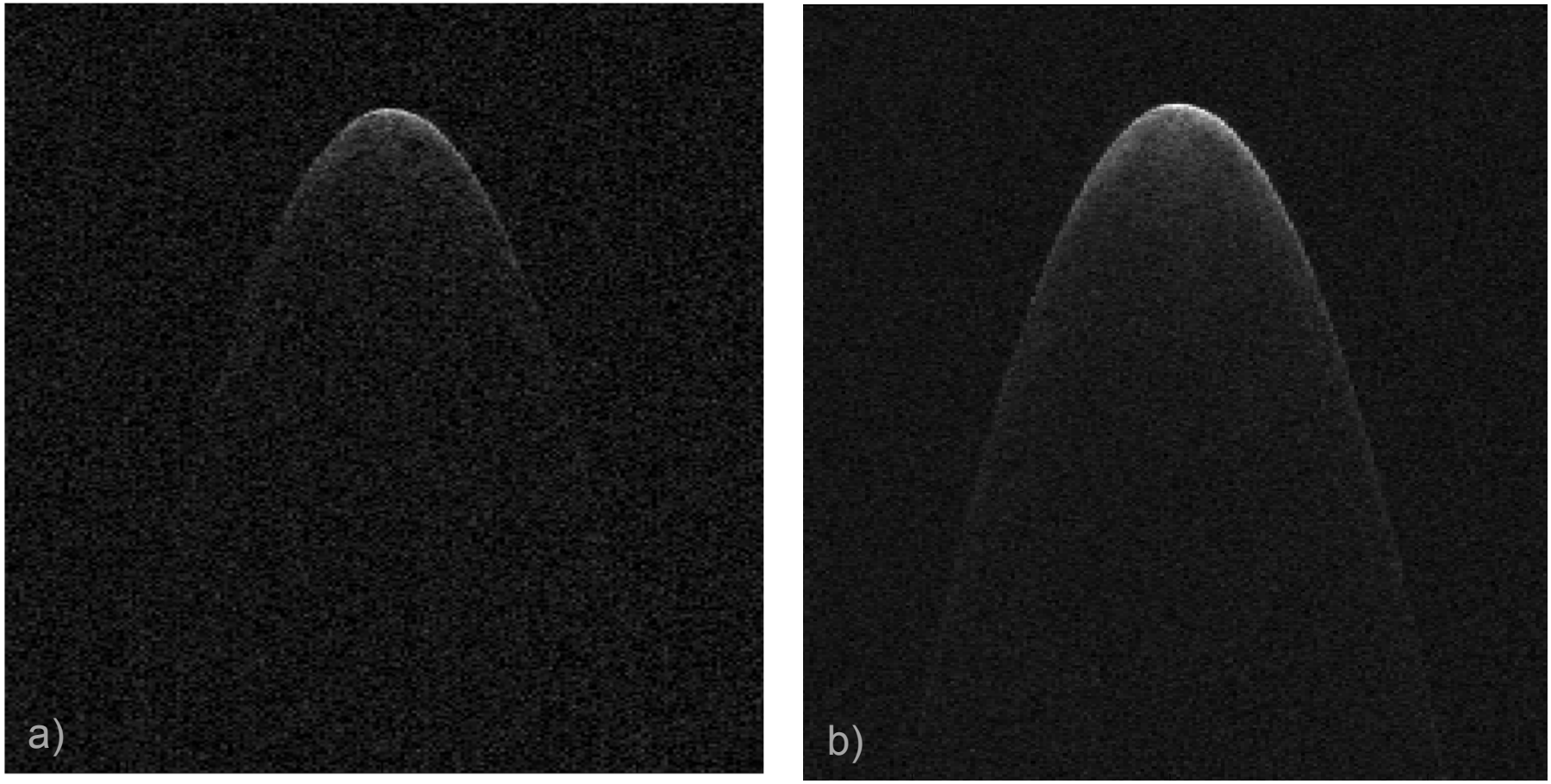

Doppler-delay images of Venus, taken on DOY-297, RSR processing (1024 FFT): a) single antenna illumination (DSS-25); b) two-antenna phased-array illumination (DSS-24 + DSS-25), showing greatly improved image quality. Range decreases along the vertical axis, Doppler increases along the horizontal axis.

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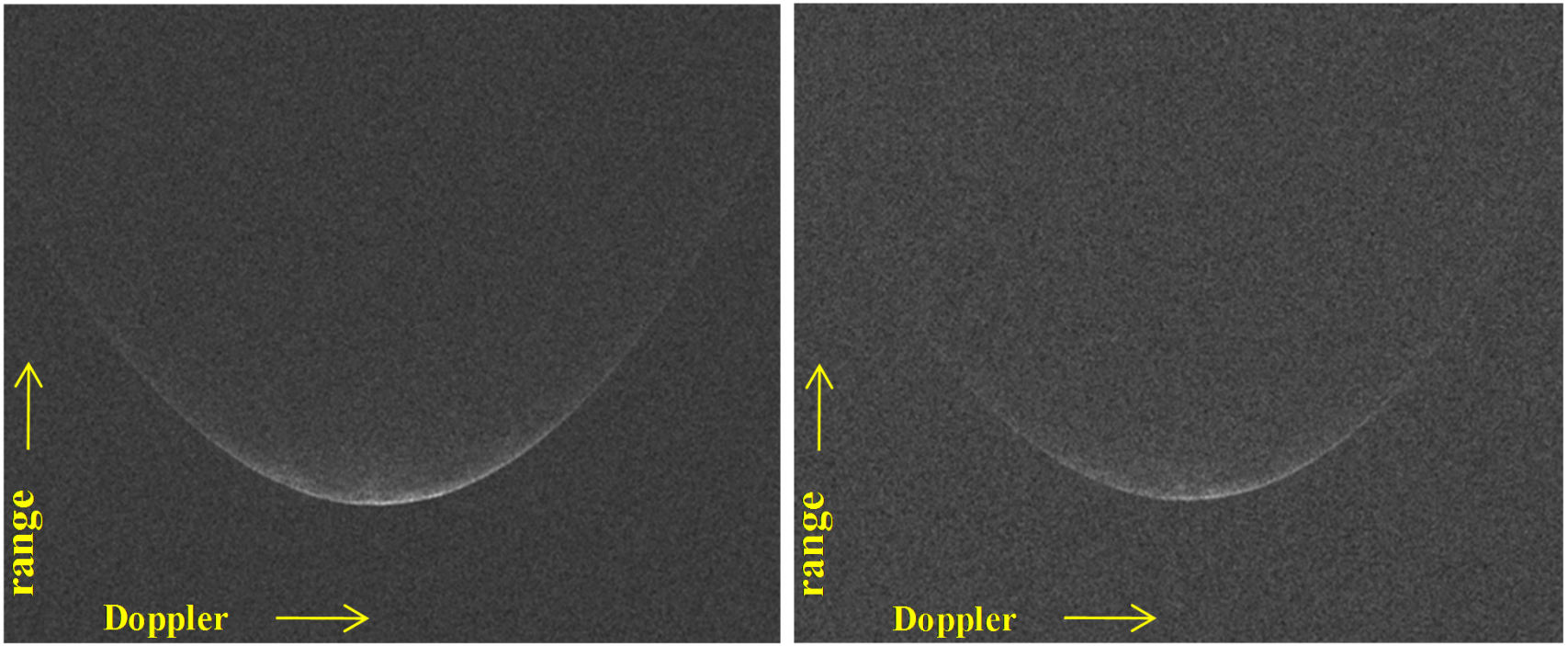

Attempted resolution of north-south ambiguity, GSSR processing (4096 FFT):

a) +90 degree phase applied, northern hemisphere,

b) -90 degree phase applied, southern hemisphere.

c) Range increases along the vertical, Doppler along the horizontal axis.

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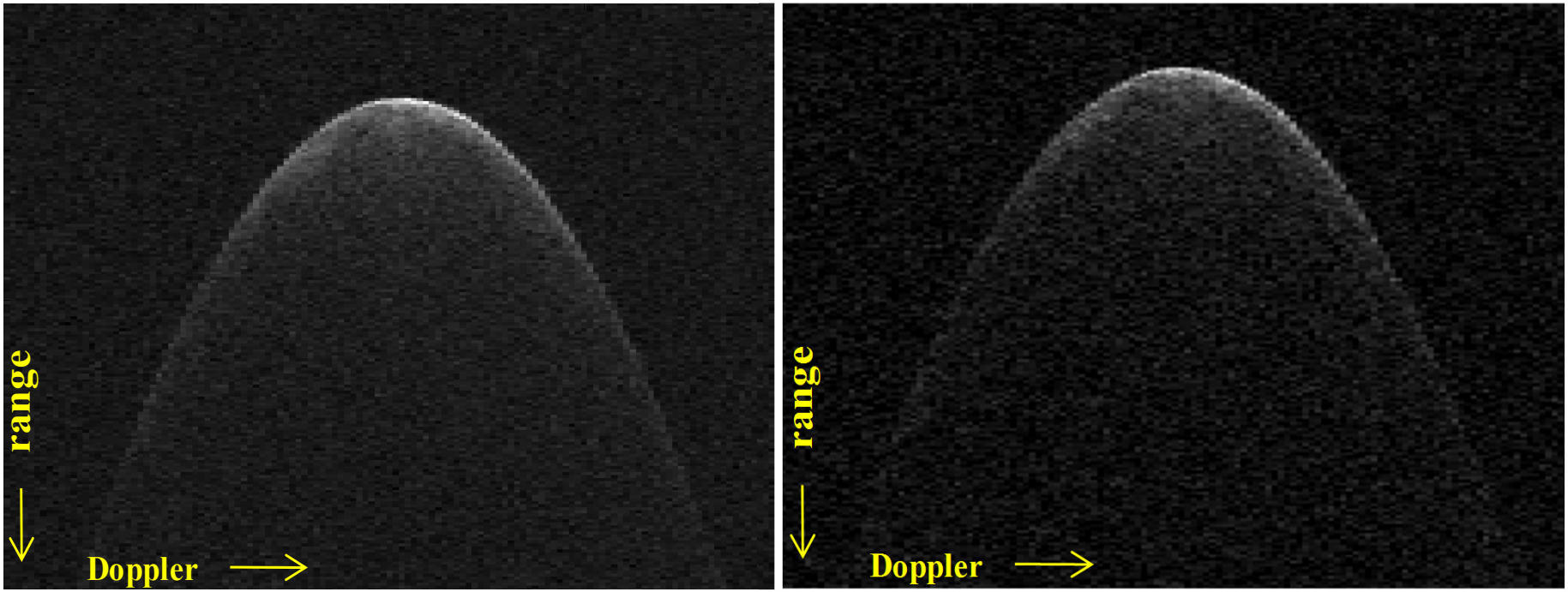

Attempted resolution of north-south ambiguity, RSR processing (1024 FFT):

a) +90 degree phase applied, northern hemisphere,

b) -90 degree applied, southern hemisphere.

Range decreases along the vertical, Doppler increases along the horizontal axis.

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Reports, Conference publications, and NTRs to date

1. V. Vilnrotter, R. Mukai, D. Lee, “Uplink Array Calibration via Far-Field Power Maximization,” IPN Progress Report 42-164, February 15, 2006.
2. NTR # 42597: “Uplink Array Calibration via Moon-Bounce Power Maximization” (Vilnrotter, Mukai, Lee)
3. JPL News Note: “JPL Performs First Two-Antenna Uplink Array Experiment” (appeared on 3/21/06)
4. NTR # 43674: “Uplink Array Calibration Using Power Measurements from a Nearby Spacecraft” (Vilnrotter, Lee, Paal, Mukai, Cornish)
5. F. Davarian, V. Vilnrotter, “Uplink Antenna Arraying for the Interplanetary Network,” 24th AIAA International Communications Satellite Systems Conference, San Diego, CA, June 13, 2006.
7. V. Vilnrotter, Dennis Lee, “Uplink Array Experiment with the Mars Global Surveyor (MGS) Spacecraft,” IPN-Progress Report 42-166, August 15, 2006.
8. L. Paal, R. Mukai, T. Cornish, V. Vilnrotter, D. Lee, “Measurement of Antenna Phases due to Ground Equipment Effects in an Uplink Array,” to appear in IPN-Progress Report 42-167, November 15, 2006.
9. L. Paal, R. Mukai, V. Vilnrotter, T. Cornish, and D. Lee, “Ground System Phase Estimation Techniques for Uplink Array Applications,” IPN Progress Report 42-167, November 15, 2006.
10. V. Vilnrotter, D. Lee, R. Mukai, T. Cornish, P. Tsao, “Three-antenna Doppler-delay Imaging Of The Crater Tycho For Uplink Array Calibration Applications,” IPN Progress Report 42-169, May 15, 2007.
11. Doppler-Delay Calibration of Uplink Arrays via Far-Field "Moon-Bounce“ Power Maximization, V. Vilnrotter, D. Lee, R. Mukai, T. Cornish, P. Tsao, 11-th ISCOPS Conference, Beijing, May 15, 2007.
12. NTR # 44611: “Ground System Phase Estimation for Uplink Arrays,” L. Paal, R. Mukai, V. Vilnrotter, T. Cornish, D. Lee, November 1, 2006.

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Reports, continued

12. NTR # 45243: "A Program for Calculating Pointing, Doppler, and delay compensation for the Moon-Bounce Experiment," V. Jamnejad, V. Vilnrotter, N. Bachman, August 2, 2007.
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