VLBA Observations of solar system objects: natural and man-made

NRAO An NSF Facility

National Radio Astronomy Observatory

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Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NSF Associated Universities, Inc. NRAO

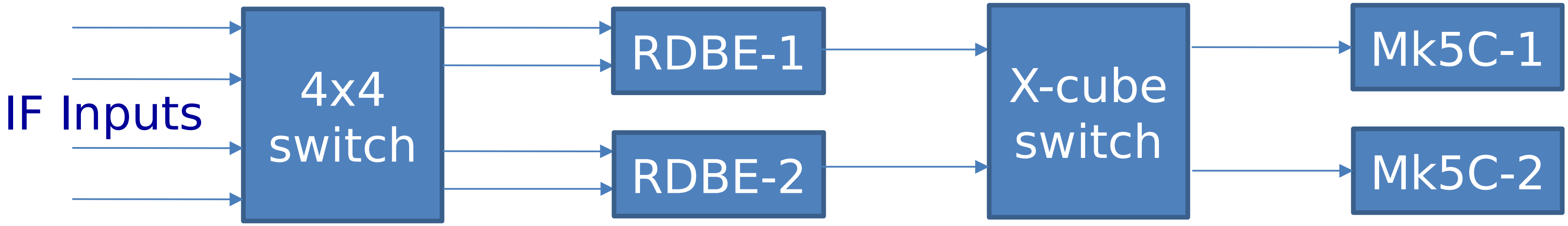
Key capabilities of the VLBA

- Ten 25-m antennas working from 0.3 to 90 GHz
- Baselines up to 8600 km
- Within the GMVA, provides the highest resolution imaging in astronomy (0.1 mas)
- Bold claim: Best astrometric telescope in existence
  - ±10 μas accuracy, *i.e.,* 10% parallax distances at 10 kpc
- Fast response to transient phenomena
- 24/7/363 Centralized operations (antennas and correlator) in Socorro
  - Simplifies flexible / dynamic scheduling
- Flexible software correlator (DiFX)

Recent VLBA developments (FY13 to FY15)

- FY2013 (Oct 1, 2012 to Sep 30, 2013)
  - Completed the Sensitivity Upgrade
  - Implemented a rapid-response capability
  - First fringes to LMT
  - Demonstration of Near-Real-Time observing
- FY2014 (Oct 1, 2013 to Sep 30, 2014)
  - Deployed new versatile tuning synthesizer at Los Alamos
  - Retired Mark5A recorders
- FY2015 (Oct 1, 2014 to Sep 30, 2015)
  - Implementing real-time software-based pulse cal extraction
  - Retiring legacy data formatter & baseband converters
  - Modernizing monitor and control of legacy hardware

Upgraded backend electronics



- 4 IFs from antenna (512 MHz bw centered on 768 MHz)
- 4x4 switch: fully general IF switch (any output can be attached to any input)
- ROACH Digital BackEnd (RDBE)
  - DDC personality: 1-4 channels, 1-128 MHz/channel, VDIF
  - PFB personality: 16 channels, 32 MHz/channel, Mark5B
  - 2x DDC for 8 channels; 512 MHz max total bandwidth; VDIF
- X-cube switch
  - Fully general 10 Gbps switch; burst mode; some local storage
- Mark5C
  - 2nd unit only at PT and MK (for USNO UT1-UTC observing)

VLBA solar system observations

- Two dedicated capability development projects
  - 2003-2004: Spacecraft Navigation Pilot Project (SNPP)
    - In collaboration with and funded by NASA
  - 2008: Phoenix navigation demonstration
- Some scientific endeavors
  - 2004: Cassini flyby of Iapetus for mass measurement (Cassini mission)
  - 2005: Huygens probe enters Titan’s atmosphere (JIVE, global VLBI)
  - 2006-current: Astrometry of Cassini for ephemeris improvements (D. Jones)
  - 2008-current: Multi-static radar observations of asteroids
- Renewed testing, demonstration of technical advances
  - 2013: Voyager I, where are you?
  - 2013: Near-Real-Time (NRT) observations of MRO and Odyssey

Spacecraft Navigation Pilot Project

- 13 test observations over 9 months (2003-2004)
  - Several spacecraft
  - Varied calibration strategy
  - Varied declination
- Total delays chosen as NRAO to NASA data product interface
  - Results independent of correlator model and ephemeris used
- Technologies developed:
  - Antenna pointing corrections for nearby objects
  - Ephemeris-driven correlator model
    - Including changes to GR light bending: spacecraft is within the solar system gravity field
  - Data processing task to export total delays from AIPS
  - Ka-band receiver w/X-band dichroic designs (not yet implemented)

Phoenix Navigation Demonstration

- 10 observations over 20 days (2008)
  - Timed for Phoenix lander encounter with Mars
  - Phase referenced to ICRF and to existing Mars orbiters
- New technologies used and developed
  - DiFX software correlator
    - Allows much more flexible correlation
    - Uses same delay model code as hardware correlator
  - Very rudimentary electronic transfer VLBI capabilities
    - Code developed to extract only 1 channel of interest from Mark5 recordings for transmission
- JPL analysis of total delays yielded 20-50 μas agreement between two spacecraft
- Precision of tie between spacecraft and ICRF not satisfactorily determined
  - Estimated to be better than or about 200 μas for sep. < 2-3 deg.

VLBA Astrometry of Cassini at Saturn

- Observing every few months since 2006
- Ongoing observations will ultimately reduce uncertainty in Saturn's position by a factor of about 3 as more of Saturn's orbit is probed.
- This will have implications for spacecraft navigation, solar system dynamics, relativity research, pulsar timing, and frame ties connecting the solar system to the ICRF.

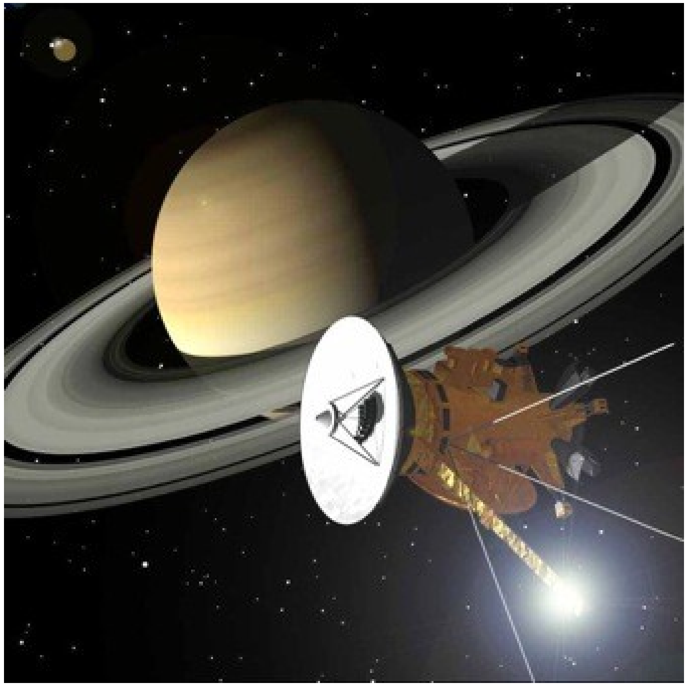
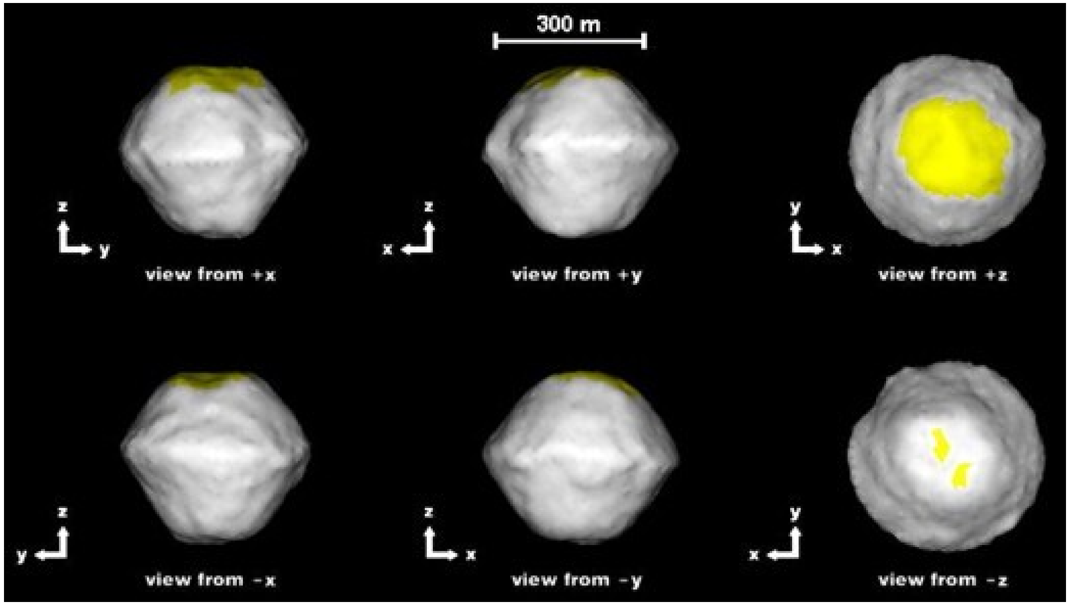


Image: NASA

Jones et al., 2011, ApJ, 141, 29

Multi-static asteroid radar

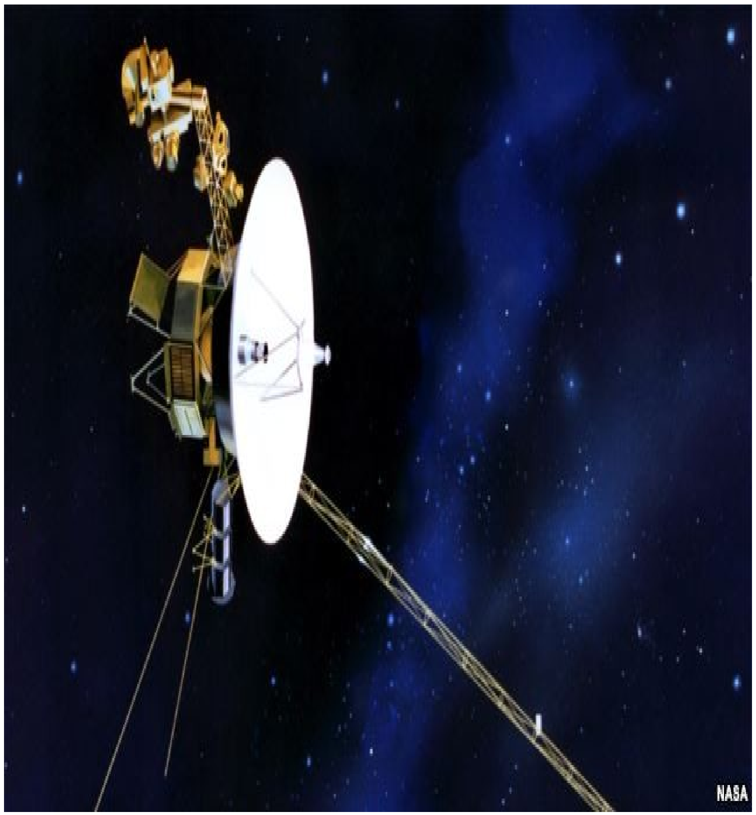
- Radar observations of astroids can provide structure, spin rates and axis orientation
- They are often insensitive to the sense of rotation
- Cross-correlation of the speckle amplitude as measured by ground stations can determine this quantity
- Arecibo + short spacings of VLBA work well for these observations
- Important for:
  - Formation studies
  - Trajectory projection
  - Saving the humans!



Busch et al., 2008, ...

Voyager 1. Where are you?

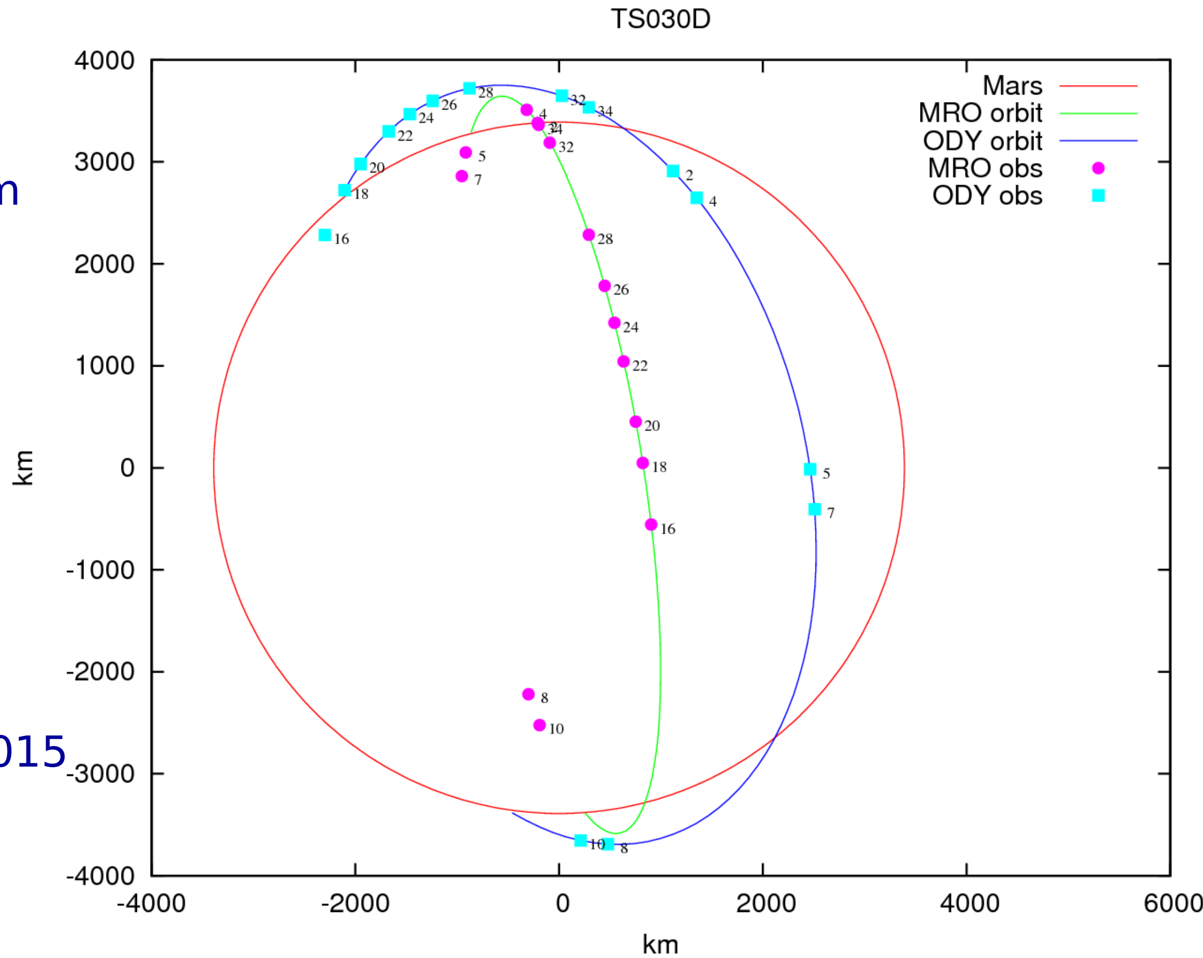
Image: T Beasley



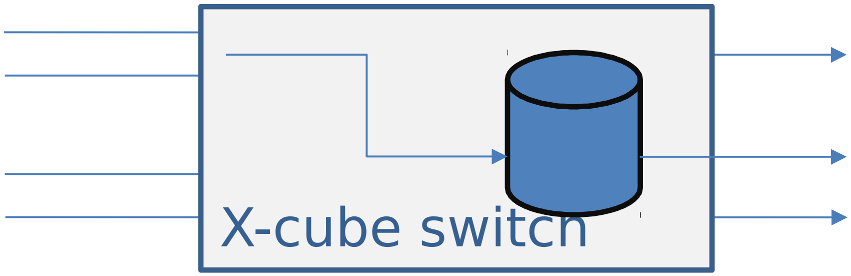
- First SC observations with RDBEs
  - Observed in narrow-band mode
    - 400 Hz channelization
  - eTransfer to Socorro for correlation
  - 2 observations: Feb and July 2013
- Voyager 1 was 0.6” off ephemeris
  - And seen to be increasing
    - Zero-offset point at Neptune?
  - Well timed w.r.t. leaving the SS
  - VLBA noted in NASA press conf.

Near-real-time spacecraft tracking demo

- Primary goal:
  - Demonstrate low latency localization
- Mars at 2.2 AU ~= 3.4e8 km
  - 1 mas = 1.6 km
  - 1 nrad = 330 m
- MRO
  - 8439.444446 MHz
  - Apogee at 3700 km
- Odyssey (ODY)
  - 8406.851853 MHz
  - Apogee at 3800 km
- Both in same VLBA beam
- See Max-Moerbeck et al., 2015



Near-real-time data transfer



- Linux-PC-based X-cube switch sees *all* baseband traffic before going to Mark5C recorder(s)
- For sufficiently low bandwidth (<~ 512 Mbps) raw network data can be captured to the internal hard drive.
- Each recording scan is captured into a separate file on the spinning disk
- Once a file stops growing (scan ends), it is immediately available for transmission, even while recording the next scan
- The Tsunami-UDP protocol, outfitted with auto-restart, is used

VLBA network connectivity

- Pie Town and Mauna Kea
  - ~300 Mbps realized on 1 Gbps links
  - Connectivity funded by USNO for their daily UT1-UTC observations
  - Wide-band NRT PT-MK baseline measurements are possible
- 8 other VLBA antennas
  - 1.1 Mbps realized on 1.4 Mbps links
    - Traffic shared with monitor and control
  - These links dominate the latency of the results
  - In 6 hours about 3GB per antenna can be transferred
    - = 50 minutes of data at 8 Mbps
    - = 12 seconds of data at full rate (2 Gbps)!

Correlation

- The VLBA DiFX correlator is used for near-real-time correlation
  - Correlation off files, not disk modules
  - Can correlate in parallel with production (module-based) correlation
  - Runs many times observe-time speed, rerun as needed
  - Run one scan at a time for SC observations
  - Predicted Earth Orientation Parameters must be used
- Correlation can proceed on partial files
  - First fringes seen within a few minutes of observation start!
- First correlate the fringe finder
  - Determine and compensate instrumental delays
- Separate correlation pass for each SC, using appropriate ephemeris
- Assemble raw output into one FITS file per SC
  - Tsys data for amplitude calibration not available until after observation
  - No need to recorrelate, just reassemble, once this data is available

Near-real-time data reduction path: Calibration

- Calibrated using AIPS
- Amplitude calibration
  - Digital sampler corrections
  - Tsys data only available after completion of observing
  - No bandpass calibration performed
    - Outer 10% of channels are excluded
- Polarization parallactic angle rotation correction
- Instrumental delay correction
  - Fringe fit on bright source at beginning of experiment
    - First 10-station fringes seen in <5 minutes from observation start
- Phase calibration uses nearby calibrator source
  - This establishes registration to the ICRF

Sensitivity considerations

- Spacecraft signals are *very* strong (even Voyager I!)
  - Precision limited by continuum calibrator sources and cross-calibration
- Angular resolution
  - 1 x 2 mas at X-band (8.4 GHz)
- 10-antenna image sensitivity
  - 5 mJy in 1 minute over 1 MHz
  - 100 mJy calibrator $\rightarrow$ SNR=20 $\rightarrow$ 25 x 50 μas accuracy
- Accurate results are possible with very little observing time
- For bright calibrator sources systematics are more important
  - Atmosphere contamination
  - Location uncertainty of calibrator sources dominates for small angles!
- Weaker calibrators can be used
  - More time on source or wider bandwidth (= more bits) required
  - Can reverse roles of calibrator and target

Conclusions

- The astrometric precision of the VLBA has been enabling studies of solar system and deep space vehicle dynamics for the past decade
- Useful near-real-time (10s of minutes latency) results have been obtained with the VLBA
- Such observations could be valuable for operators of interplanetary spacecraft
- Solar system VLBI offers huge potential for innovation
  - All projects to date have required some degree of technical development
  - The surface has just been scratched!

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