Radar as a tool to study the Solar System

GBT/AO Single Dish Workshop
September 16, 2021

Maxime Devogèle
Planetary Radar Science Group
Outline

• What is a radar system and why do we use it for Solar System studies
• Introduction to Radar Systems and observing methods
• Results from planetary radar observations
• Introduction to Solar System radar data processing

Image credit: Bruce Campbell (Smithsonian Institute)
What is RADAR?

• RAdio Detection And Ranging
• Active remote sensing – we control the signal!
• Maximize signal properties to enhance SNR
• Measure reflected radio waves (so targets must be reflective)

Image source: https://en.wikipedia.org/wiki/Klystron
What is RADAR?

- **RA**dio **D**etection **A**nd **R**anging
- Active remote sensing – we control the signal!
- Maximize signal properties to enhance SNR
- Measure reflected radio waves (so targets must be reflective)

Image source: https://en.wikipedia.org/wiki/Klystron

Solid State Amplifier
Why use radar to observe objects in space?

- Penetrate through atmospheres
- Reveal buried features
- Use polarimetry to detect surface properties
- Image at resolutions comparable to space missions

Image credits:
- Image at resolutions comparable to space missions: NASA/NSF
- Penetrate through atmospheres: Lynn Carter (LPL)
- Reveal buried features: Bruce Campbell (Smithsonian Institute)
- Use polarimetry to detect surface properties: G. Wes Patterson (JHU/APL)
- Image at resolutions comparable to space missions: (163899) 2003 SD220

Arecesbo Observatory - Green Bank
NASA/NSF
18 December 2018

Oceanus Procellarum
Kepler
Astrometry: refining orbits of celestial bodies

- Range (distance) resolution as fine as ~5 m
- Relative velocity resolution as fine as ~10 mm/s

Image credit: https://ssd.jpl.nasa.gov/sbdb.cgi#top
Astrometry: refining orbits of celestial bodies

Image credit: Jon Giorgini (JPL)
Astrometry: refining orbits of celestial bodies

Image credit: Jon Giorgini (JPL)
Astrometry: refining orbits of celestial bodies

Uncertainty Region for Asteroid 2021QM1
(relative to the nominal observation)
Date and time 2021/09/30 18:55:00 UTC, Sigma level 3.0

Stars
- mag > 19
- 18 < mag <= 19
- 17 < mag <= 18
- 16 < mag <= 17
- 15 < mag <= 16
- 14 < mag <= 15
- 13 < mag <= 14
- 12 < mag <= 13
- mag <= 12

Background stars are provided by the GAIA DB query (EDR3).

Image credit: Jon Giorgini (JPL)
Astrometry: refining orbits of celestial bodies

Image credit: Jon Giorgini (JPL)
Astrometry: refining orbits of celestial bodies

Image credit: Jon Giorgini (JPL)
Astrometry: refining orbits of celestial bodies

Image credit: Jon Giorgini (JPL)
Astrometry: refining orbits of celestial bodies

Image credit: Jon Giorgini (JPL)
Arecibo, Goldstone, GBT

- Declination range: -35°–90° (79% of the whole sky)
- Several antennas (the largest, DSS-14: 70 m)
- Transmitter frequency: 8560 MHz (3.5 cm)
- Power up to 500 kW
- ~70 objects/year attempted, ~60 detected

Goldstone Solar System Radar

- Declination range: -1–38 (32% of the whole sky)
- 305 m antenna
- Transmitter frequency: 2380 MHz (12.6 cm)
- Power up to 1 MW
- ~100 objects/year attempted, ~80 detected

Image credit: NASA/JPL-Caltech
• Declination range: -46°–90° (86% of the whole sky)
• 100m antenna

Green Bank
The Radar Equation

\[ P_{rx} = \begin{bmatrix} P_{tx} \\ G_{tx} \end{bmatrix} \begin{bmatrix} 1 \\ \frac{1}{4\pi r^2} \end{bmatrix} \begin{bmatrix} \sigma \\ \frac{1}{4\pi r^2} \end{bmatrix} \begin{bmatrix} A_{eff} \end{bmatrix} \]

- Received Power
- Transmitted Power
- Transmitter Gain
- Radar Cross Section
- Geometric Spreading
- Effective Aperture

Image credit: JAXA
Continuous Wave (CW) signals:

- This is when we transmit a continuous signal with a constant amplitude, phase, and frequency.
- We cannot differentiate signals based on when they arrive (no range information). This only gives us information on the shift in frequency, or Doppler shift of the reflected signal, based on the motion of the target.
Continuous Wave (CW)

- **Continuous Wave (CW) signals:**
  - This is when we transmit a continuous signal with a **constant amplitude, phase, and frequency**.
  - We cannot differentiate signals based on when they arrive (no range information). This only gives us information on the shift in frequency, or Doppler shift of the **reflected signal**, based on the motion of the target.
Continuous Wave (CW)

- **Continuous Wave (CW) signals:**
  - This is when we transmit a continuous signal with a **constant amplitude, phase, and frequency.**
  - We cannot differentiate signals based on when they arrive (**no range information**). This only gives us information on the shift in frequency, or Doppler shift of the reflected signal, based on the motion of the target.
• Target’s doppler bandwidth depends on size and spin state:

\[ B = \frac{4\pi D \cos \phi}{\lambda_0 P_{\text{spin}}} \]
Target’s doppler bandwidth depends on size and spin state:

\[ B = \frac{4\pi D \cos \phi}{\lambda_0 P_{\text{spin}}} \]

Doppler equation:

\[ f_0 = \left(1 \pm \frac{2v}{c}\right)f_e \]

\[ v = \frac{\pi D}{P} \quad f_e = \frac{c}{\lambda} \]

\[ B = \frac{2v}{c}f_e - \left(-\frac{2v}{c}f_e\right) \]

\[ B = \frac{4\pi D}{\lambda P} \]
Target’s doppler bandwidth depends on size and spin state:

\[ B = \frac{4\pi D \cos\phi}{\lambda_0 P_{\text{spin}}} \]

RMS noise power depends on bandwidth, integration time, and system temperature:

\[ N_{\text{rms}} = k T_{\text{sys}} \sqrt{\frac{B}{\tau}} \quad \text{k = Boltzmann’s constant} \]
• Target’s doppler bandwidth depends on size and spin state:

\[ B = \frac{4\pi D \cos \phi}{\lambda_0 P_{\text{spin}}} \]

• RMS noise power depends on bandwidth, integration time, and system temperature:

\[ N_{\text{rms}} = k T_{\text{sys}} \sqrt{\frac{B}{\tau}} \]

k = Boltzmann’s constant

• Need SNR of ~6 for detection, but much higher SNR for imaging

\[ SNR = \frac{P_{rx}}{N_{\text{rms}}} \]

\[ P_{rx} = \frac{P_{tx} G_{tx} \sigma A_{\text{eff}}}{(4\pi)^2 r^4} \]
\[ B = \frac{4\pi D \cos \phi}{\lambda_0 P_{\text{spin}}} \]

- Target’s doppler bandwidth depends on size and spin state:

\[ P_{\text{rx}} = [P_{\text{tx}}] [G_{\text{tx}}] \begin{bmatrix} \frac{1}{4\pi r^2} \\ [\sigma] \end{bmatrix} \begin{bmatrix} \frac{1}{4\pi r^2} \\ [A_{\text{eff}}] \end{bmatrix} \]

- RMS noise power depends on bandwidth, integration time, and system temperature:

- Need SNR of \(~6\) for detection, but much higher SNR for imaging:

\[ \text{SNR} = \frac{P_{\text{rx}}}{N_{\text{rms}}} \]

\[ P_{\text{rx}} = \frac{P_{\text{tx}} G_{\text{tx}} \sigma A_{\text{eff}}}{(4\pi)^2 r^4} \]
SNR: Detectability

- Target’s doppler bandwidth depends on size and spin state:
  \[ B = \frac{4\pi D \cos \phi}{\lambda_0 P_{\text{spin}}} \]

- RMS noise power depends on bandwidth, integration time, and system temperature:
  \[ N_{\text{rms}} = k T_{\text{sys}} \sqrt{\frac{B}{\tau}} \quad \text{where} \quad k = \text{Boltsmann’s constant} \]

- Need SNR of ~6 for detection, but much higher SNR for imaging:
  \[ SNR = \frac{P_{\text{rx}}}{N_{\text{rms}}} \]
  \[ P_{\text{rx}} = \frac{P_{\text{tx}} G_{\text{tx}} \sigma A_{\text{eff}}}{(4\pi)^2 r^4} \]
SNR: Detectability

- Need SNR of ~6 for detection, but much higher SNR for imaging

\[
N_{\text{rms}} = kT_{\text{sys}} \sqrt{\frac{B}{\tau}} \\
B = \frac{4\pi D \cos \phi}{\lambda_0 P_{\text{spin}}} \\
Prx = \frac{P_{tx} G_{tx} \sigma A_{\text{eff}}}{(4\pi)^2 r^4} \\
SNR = \frac{Prx}{N_{\text{rms}}} \\
SNR \sim (\text{System factor})(\text{Target factor}) \sqrt{\Delta t}
\]

System factor \sim \frac{P_{tx} G_{ant} A_{\text{eff}}}{T_{\text{sys}}^{1/2}}

Target factor \sim \frac{\delta D^{3/2} P^{1/2}}{r^4}

\hat{\delta} = \text{radar albedo}
For every CW detection we learn:

- **Astrometry**: $\sim 30$ Hz offset in line-of-sight velocity of target
- **Rotation rate**: estimate from bandwidth and size

\[ B = \frac{4\pi D \cos \phi}{\lambda_0 P_{\text{spin}}} \]

- **CPR**: related to surface roughness and composition
Coded (modulated) signals:

- By adding some code, or time structure, to the transmitted signal, either by varying the frequency, phase, or amplitude, we can determine ranges of targets, or what distances from the telescope different portions of the signal were reflected from.

- Convolve received signal with transmitted signal in matched filter.
Coded Waveforms

- **Coded (modulated) signals:**
  - By adding some code, or time structure, to the transmitted signal, either by varying the frequency, phase, or amplitude, we can determine ranges of targets, or what distances from the telescope different portions of the signal were reflected from.

  - Convolve received signal with transmitted signal in matched filter.
One baud, defined as the length of time between phase shifts

\[ \Delta r = \frac{c \cdot \text{baud}}{2} \]

- Code Bandwidth = \( \frac{1}{[\text{baud}][\text{codelength}]} \)
delay-Doppler Imaging

- Splitting signal into discrete range & frequency bins
- Requires high SNR

Credit: Eric De Jong, Shigeru Suzuki, and Steven Ostro

Time Delay: Distance
- Vertical axis
- Increasing downward
- Points at the top are closest to the observer

Doppler Frequency: Velocity
- Horizontal axis
- Increasing to the right
- Points on the right are approaching the observer
3D – 2D ambiguity

**Circles:** points at the same distance (range) from observer

**Vertical Lines:** points of constant Doppler shift

Blue dots are *blue shifted*, red dots are *red-shifted*, green dots are not Doppler shifted

![Diagram](image.png)

The two blue and red dots map to the same point in a radar image (north/south ambiguity)

*Courtesy Patrick Taylor (LPI/USRA)*
Arecibo Observatory detects and characterizes ~100 near-Earth objects (NEOs) per year
Arecibo Observatory was detecting and characterizing ~100 near-Earth objects (NEOs) per year.
Arecibo Observatory was detecting and characterizing ~100 near-Earth objects (NEOs) per year.

Near-Earth Asteroids Discovered
Most recent discovery: 2020-Oct-06

Cumulative Number Discovered

Discovery Date


0 5000 10000 15000 20000 25000 30000

- All
- 140m+
- 1km+

Attempted NEAs
Detected NEAs
PHA

Gregorian dome installed
Arecibo Observatory was detecting and characterizing ~100 near-Earth objects (NEOs) per year.
2017 YE5

- Equal mass binary (only four known NEAs!)
- 7.5 m/pixel
- 20-24 hr period
- Albedo difference between bodies
- PHA
- Contact binary
  ~15% of NEAs
- 7.5 m/pixel
- ~870 m
- 4.5 hr rotation period
3200 Phaethon

- 2nd largest PHA known
- 75 m/pixel
- ~ 6 km
- 3.6 hr rotation period
- Surface features visible (crater or boulder?)
- Target of JAXA’s DESTINY+ mission set to launch 2022

Didymos

- PHA
- Binary system
- 7.5 m/pixel
- ~ 760 m
- 2.3 hr rotation period
- Target of NASA’s DART mission
• Observed April 2020
• PHA
• 7.5 m/pixel
• ~2.3 km
• 4 hr rotation period
• Prominent crater visible in the "leading edge"
Science Return

- Precise astrometry
- Surface Properties
- Discover binary asteroids
- Shape and spin state
  - Recently confirmed by NASA’s OSIRIS-REx mission to 101955 Bennu
In the late 1960's Arecibo data determined the rotation rate to be 59 days, as opposed to 88 days previously accepted!

Strong reflections from craters at the poles indicate water ice.
Venus

- Thick cloudy atmosphere and intense pressure and temperature at surface makes optical/infrared remote sensing and landing missions difficult.
- Radar penetrates clouds, revealing surface and sub-surface features.

Image credit: Bruce Campbell (Smithsonian Institute)
• Determination of the core size, spin period, spin period variation, precession rate

Spin state and moment of inertia of Venus (Margot et al. 2021)

Image credit: Bruce Campbell (Smithsonian Institute)