SDSS21: Radar Data Processing Overview

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The Arecibo Observatory and The University of Central Florida

UNIVERSITY OF CENTRAL FLORIDA

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Background Info

Historic AO Radar:

- Transmits at 2380 MHz
- Can observe if we have an ephemeris that can determine location within 2 arcminutes
- Two main types of data - CW and ranging - uncoded and binary phase coded


Courtesy Flaviane Venditti (AO/UCF)

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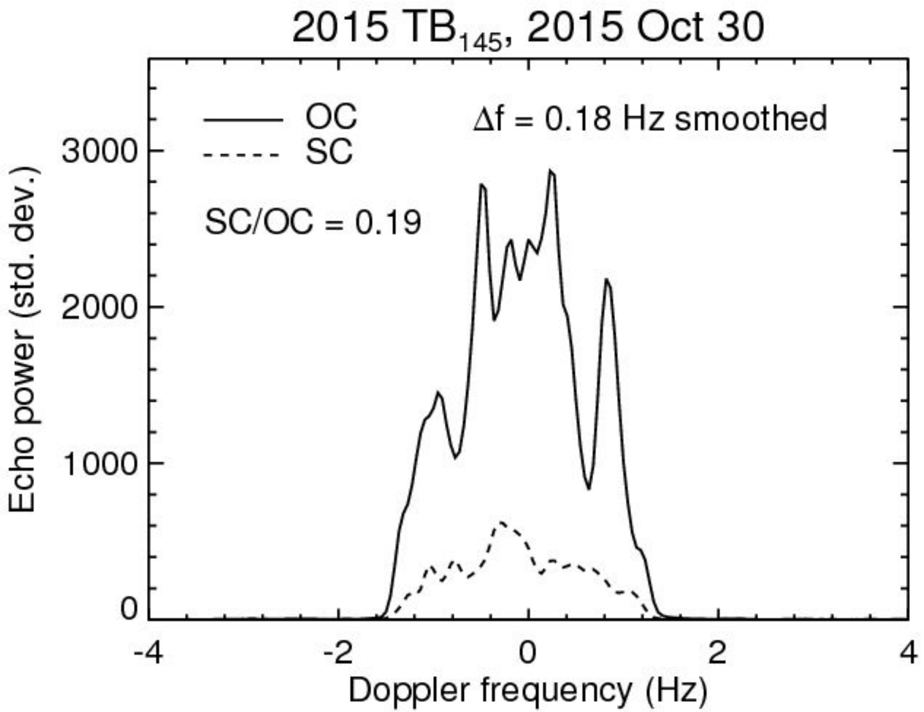
Expanding on Data Types and Datataking Systems

- Data Types
  - CW data
    - For faint targets this is often the only type we can get
    - No ranging information, only doppler frequency



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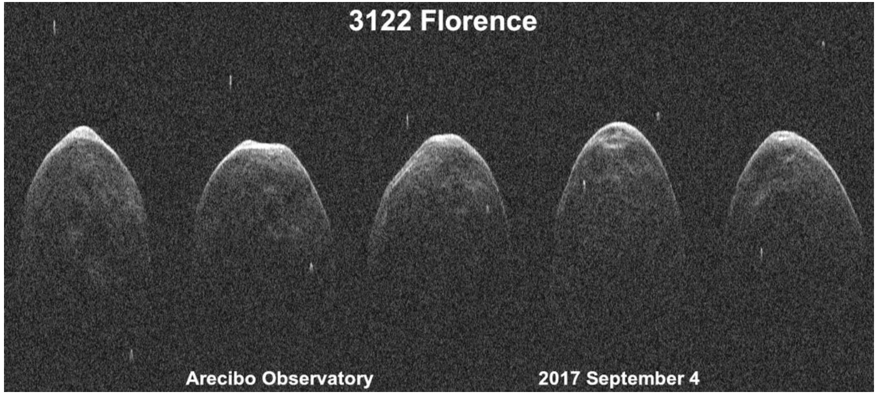
Expanding on Data Types and Datataking Systems

- Data Types
  - CW data
    - For faint targets this is often the only type we can get
    - No ranging information, only doppler frequency
  - Delay Doppler
    - Requires a higher signal to noise ratio (SNR) than cw
    - Can give ranging information on target
    - Can make images



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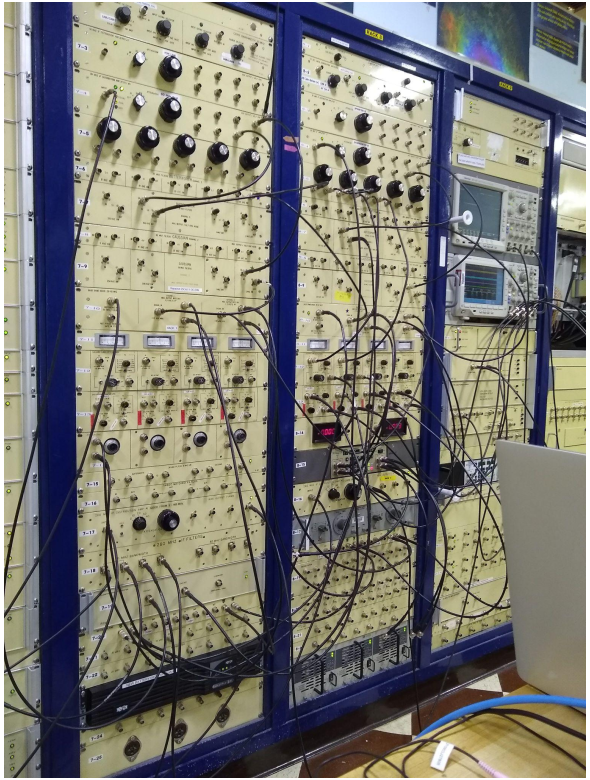
Expanding on Data Types and Datataking Systems

- AO has different data-taking systems for different purposes:
  - RI - Radar Interface
    - Primarily for cw, can do coarse imaging (ranging)
  - GIO - General In/Out Interface
    - Semi-coarse imaging (baud of 0.5 microsec or more; range resolution of ≥75 m/pixel)
    - Can do cw as well
  - PFS - Portable Fast Sampler
    - 0.05 to 0.20 microsec baud; range resolution of 7.5 to 30 m/pixel



Courtesy Flaviane Venditti (AO/UCF)

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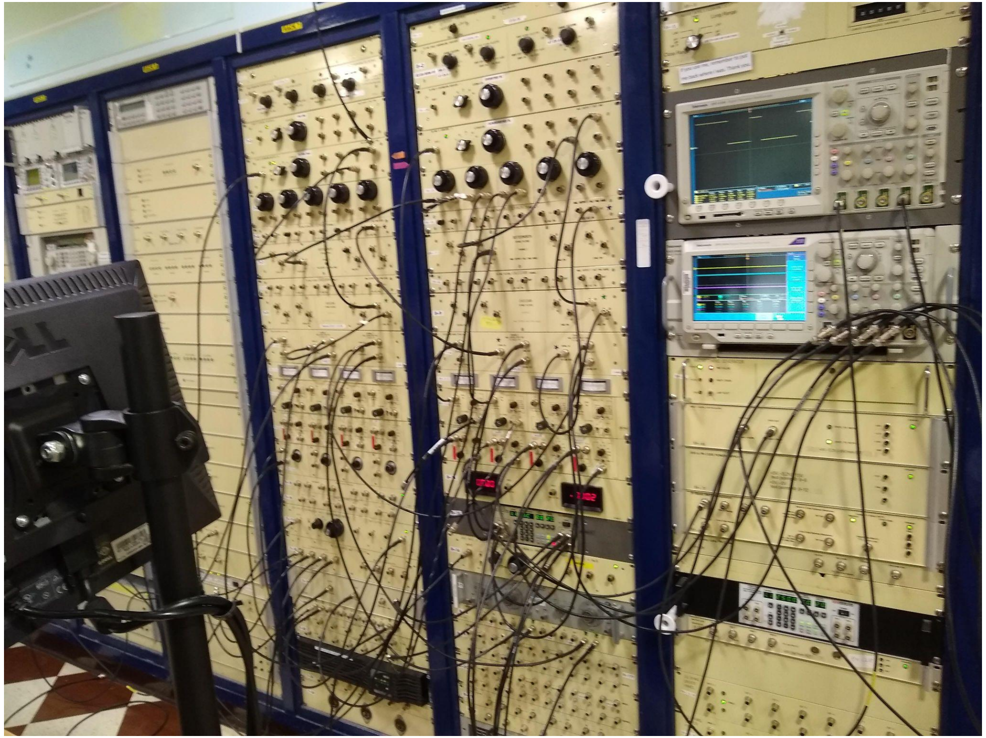
Cabling

- Radar observations are very hands on/active
- Different configurations required for each type of data
- Needs a human to physically be there doing stuff
- Goldstone is the same way - people still have to do this!



Courtesy Flaviane Venditti (AO/UCF)

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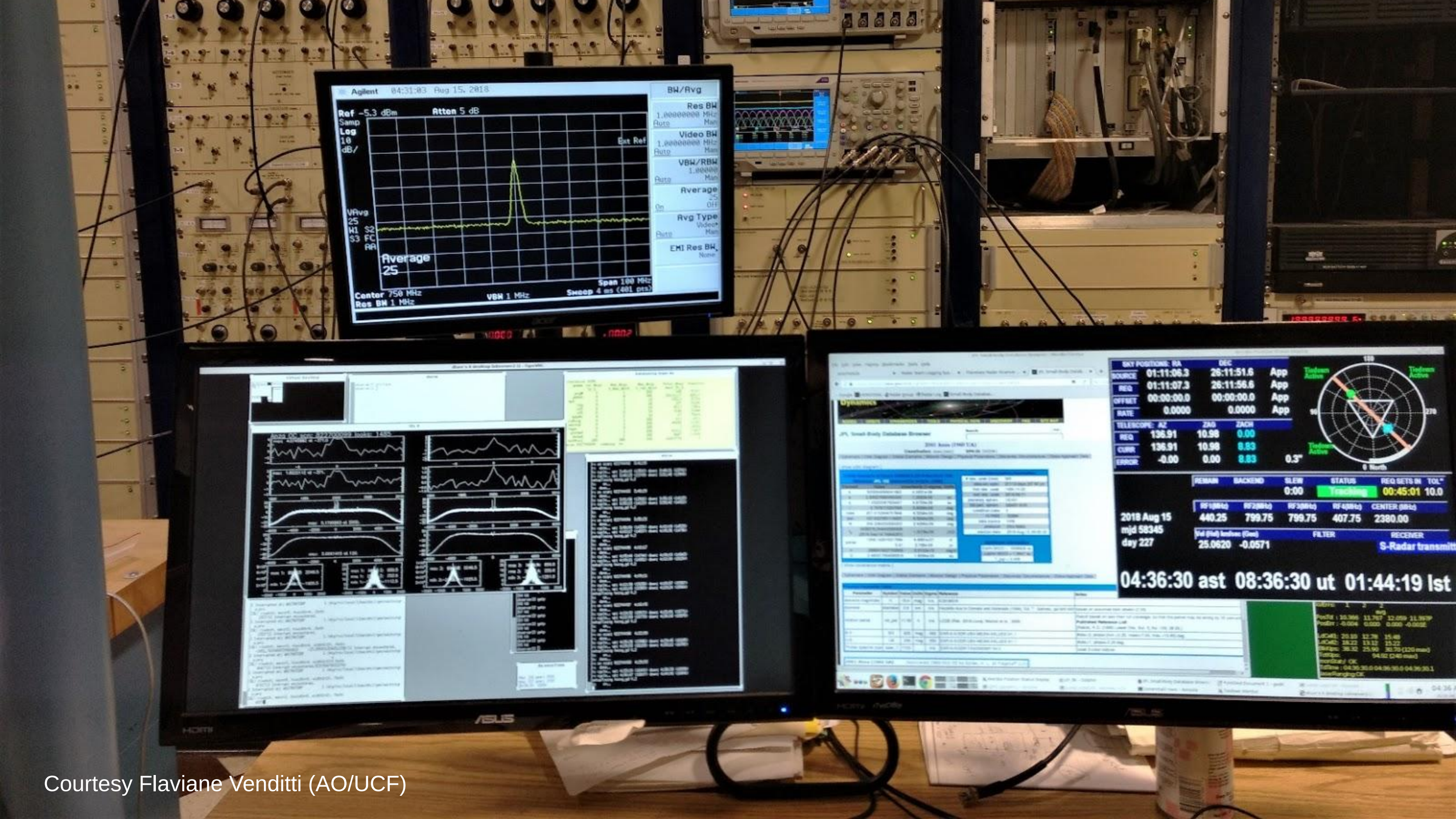


Courtesy Flaviane Venditti (AO/UCF)

CW Processing I

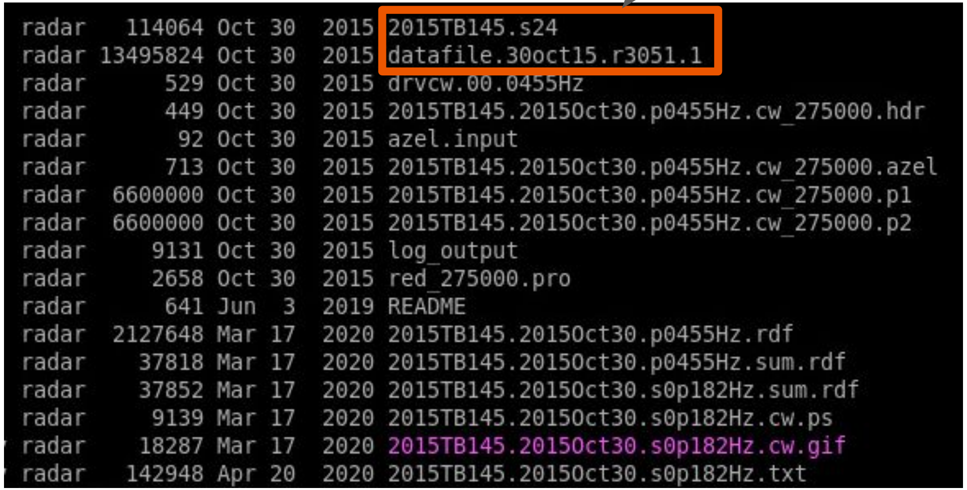
Let's run through CW datataking and processing for a single target

We'll then look at a couple different targets' output plots from the cw processing and compare them

Target we are starting with:

2015 TB145

Ephemeris and raw datafile



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CW Processing II

Once we have actually received the data, we have multiple routines to actually process it. We start by creating several different types of files using this command:

```
chris_craft datafile.30oct15.r3051 2015TB145.s24 | tee log_output
```

The most important file being one that we can use as a script to generate a plot of the cw data - shown here:

```
radar    114064 Oct 30  2015 2015TB145.s24
radar 13495824 Oct 30  2015 datafile.30oct15.r3051.1
radar       529 Oct 30  2015 drvcw.00.0455Hz
radar       449 Oct 30  2015 2015TB145.2015Oct30.p0455Hz.cw_275000.hdr
radar        92 Oct 30  2015 azel.input
radar       713 Oct 30  2015 2015TB145.2015Oct30.p0455Hz.cw_275000.azel
radar   6600000 Oct 30  2015 2015TB145.2015Oct30.p0455Hz.cw_275000.p1
radar   6600000 Oct 30  2015 2015TB145.2015Oct30.p0455Hz.cw_275000.p2
radar      9131 Oct 30  2015 log_output
radar      2658 Oct 30  2015 red_275000.pro
radar       641 Jun  3  2019 README
radar   2127648 Mar 17  2020 2015TB145.2015Oct30.p0455Hz.rdf
radar     37818 Mar 17  2020 2015TB145.2015Oct30.p0455Hz.sum.rdf
radar     37852 Mar 17  2020 2015TB145.2015Oct30.s0p182Hz.sum.rdf
radar      9139 Mar 17  2020 2015TB145.2015Oct30.s0p182Hz.cw.ps
radar     18287 Mar 17  2020 2015TB145.2015Oct30.s0p182Hz.cw.gif
radar    142948 Apr 20  2020 2015TB145.2015Oct30.s0p182Hz.txt
```

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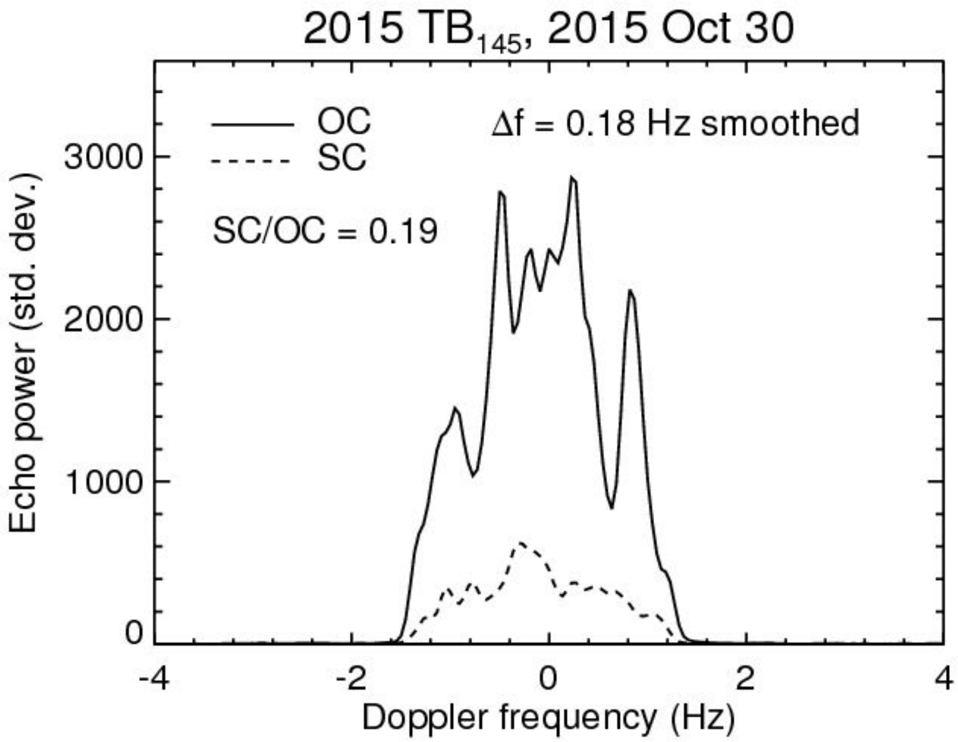
CW Processing III

- Running the IDL script will lead the user through the creation of a plot such as the one shown here
- Can change smoothing, range of plot
- This is what we use on our information page detailing what targets have been observed by AO Radar
- We can use this to determine if there is an ephemeris offset - this target is pretty well centered



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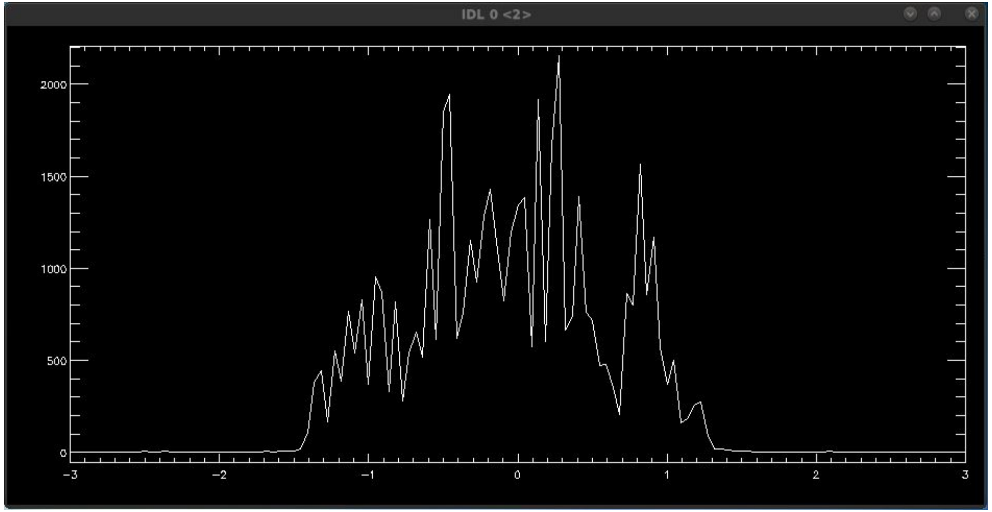
CW Processing IV

To get the most precise measurement we actually use another idl script called cwcross, which allows the user to select the exact points in a generated plot where the signal can be seen. The script then calculates things such as the bandwidth, sc/oc ratio, and the snr



CW Processing IV

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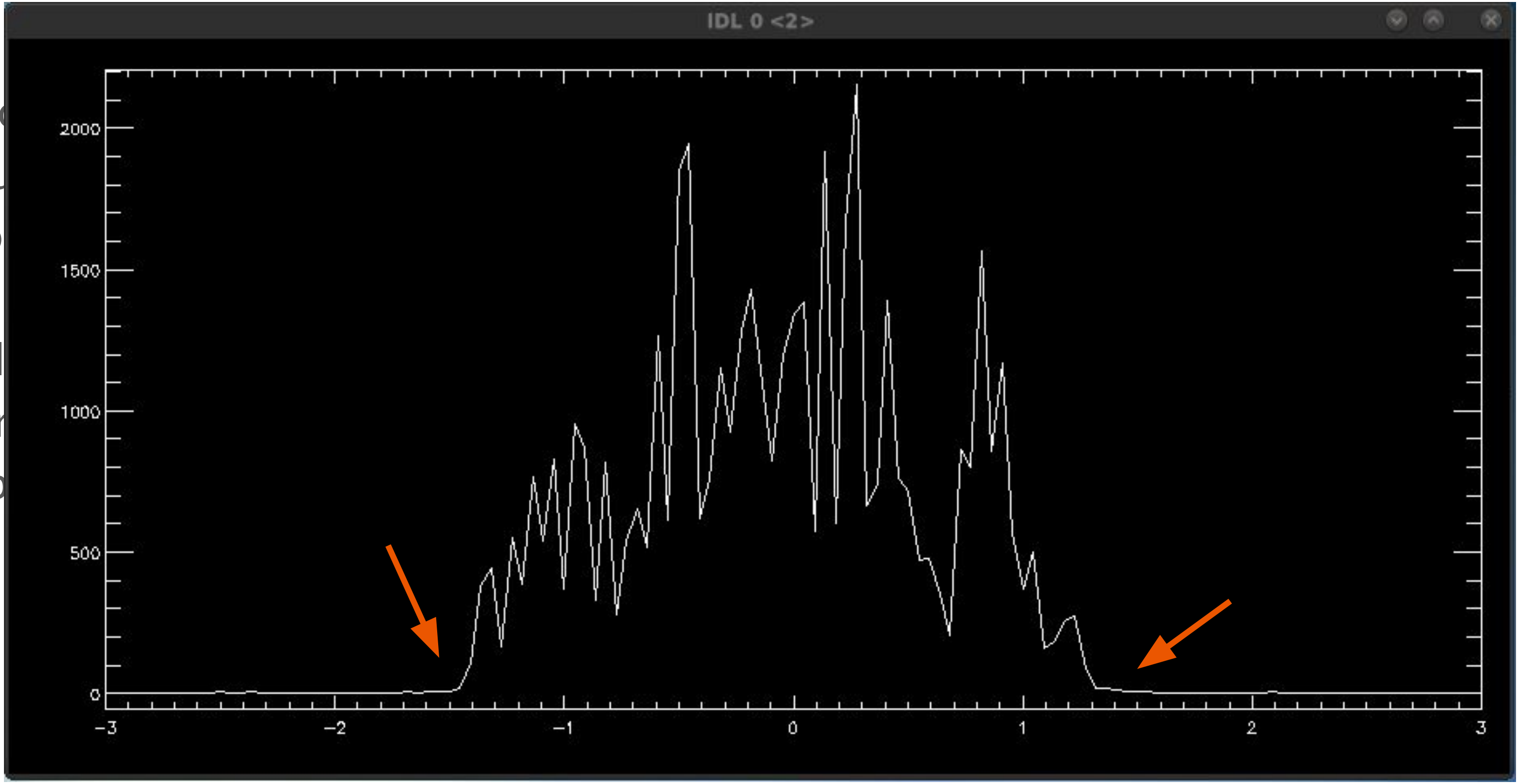
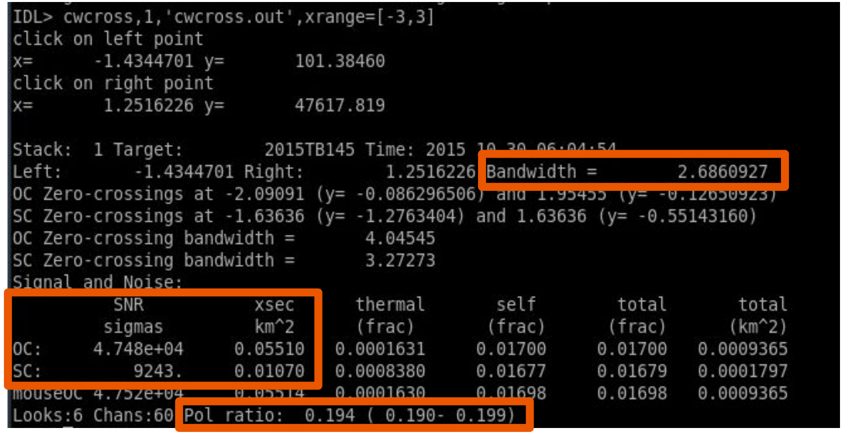
the snr



CW Processing V

The output plot from the red_####.pro script is what we use to update our information page on what we have observed, but to get the most precise measurement we actually use another idl script called cwcross, which allows the user to select the exact points where the signal can be seen. The script then calculates things such as the bandwidth, sc/oc ratio, the cross sections, and the SNR



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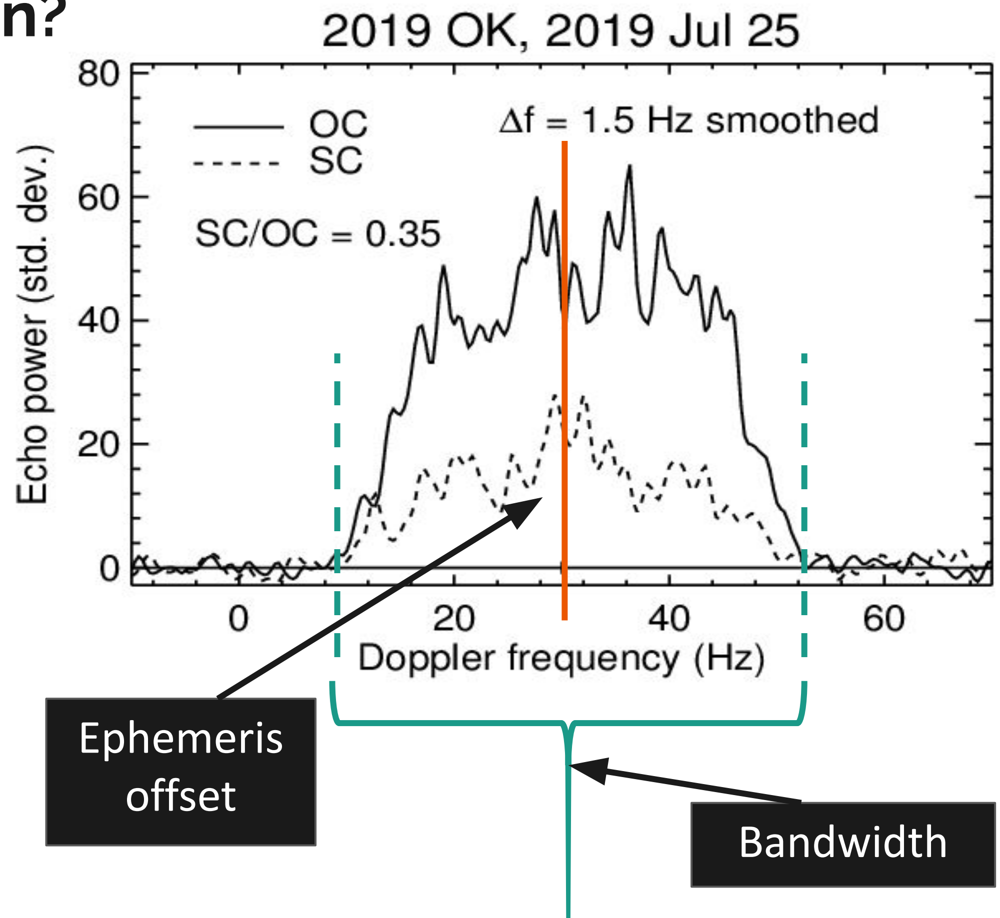
What does all that mean?

- Ephemeris offset - how far away from predicted the target was - we can make new ephemeris files with this to make more precise location predictions
- Bandwidth - this can tell us about the rotation period/size of the target

$$B = \frac{4\pi D cos\phi}{\lambda_0 P_{spin}}$$



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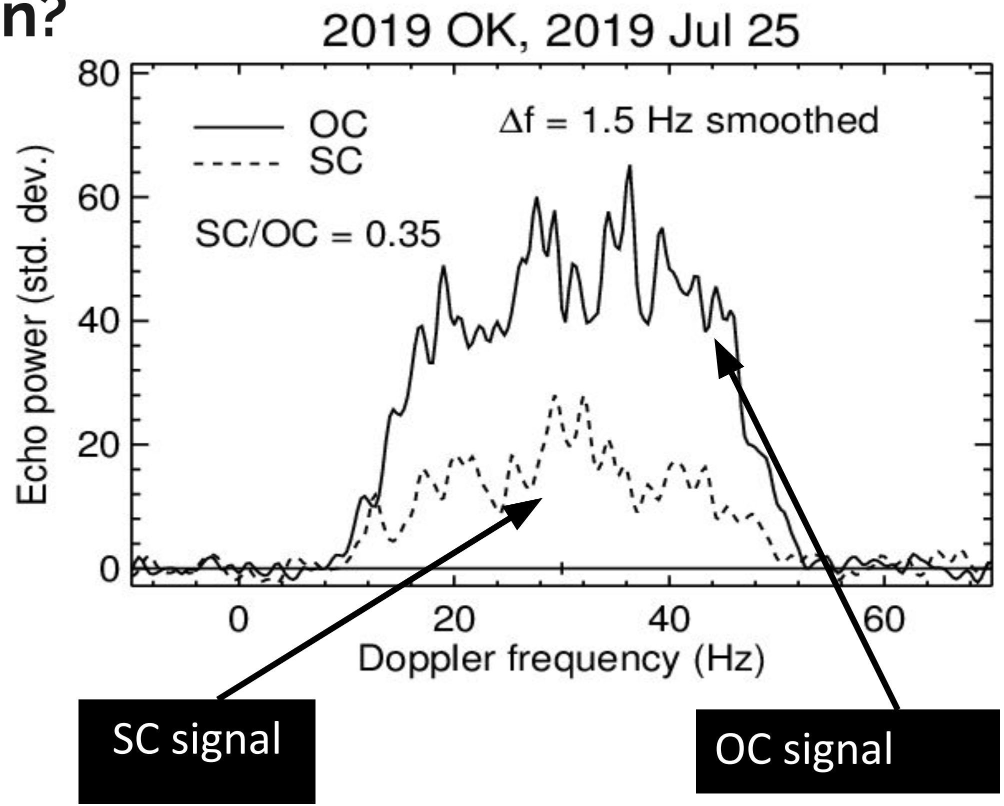
What does all that mean?

- SC/OC ratio, the ratio of same circular polarization in the return signal over the opposite circular polarization in the return signal
- an idea of the surface characteristics - High SC/OC could indicate that there is a relatively rough surface



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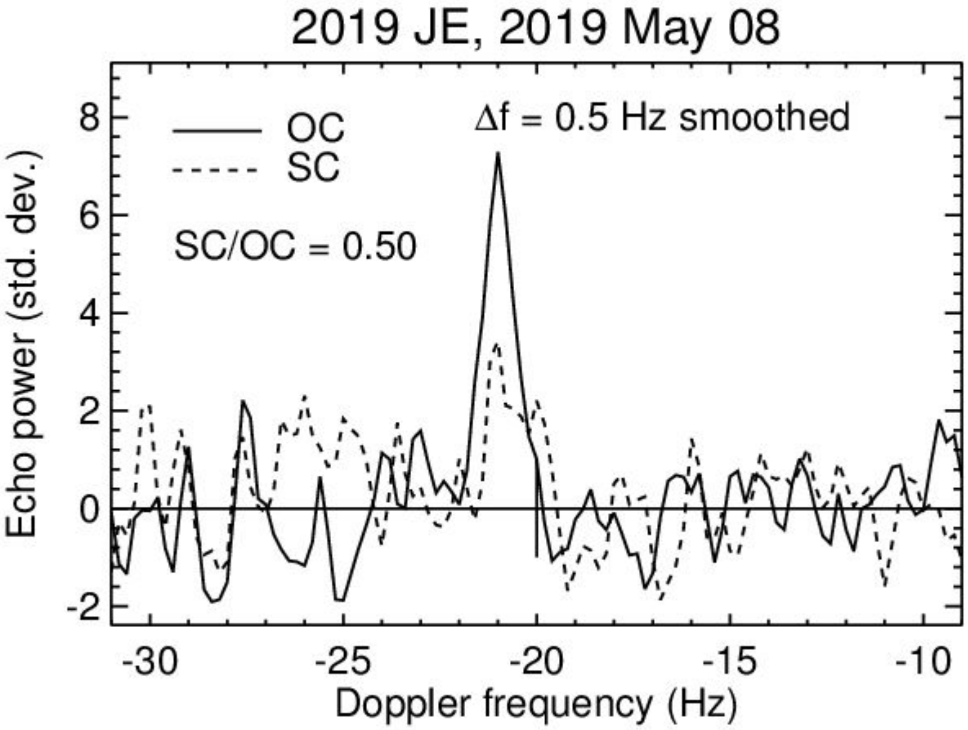
More Plots!

- This one is an unresolved target
- Only one point of data with a clear signal, means that the real bandwidth is something even lower than this
- Above 6 SNR is typically considered a detection



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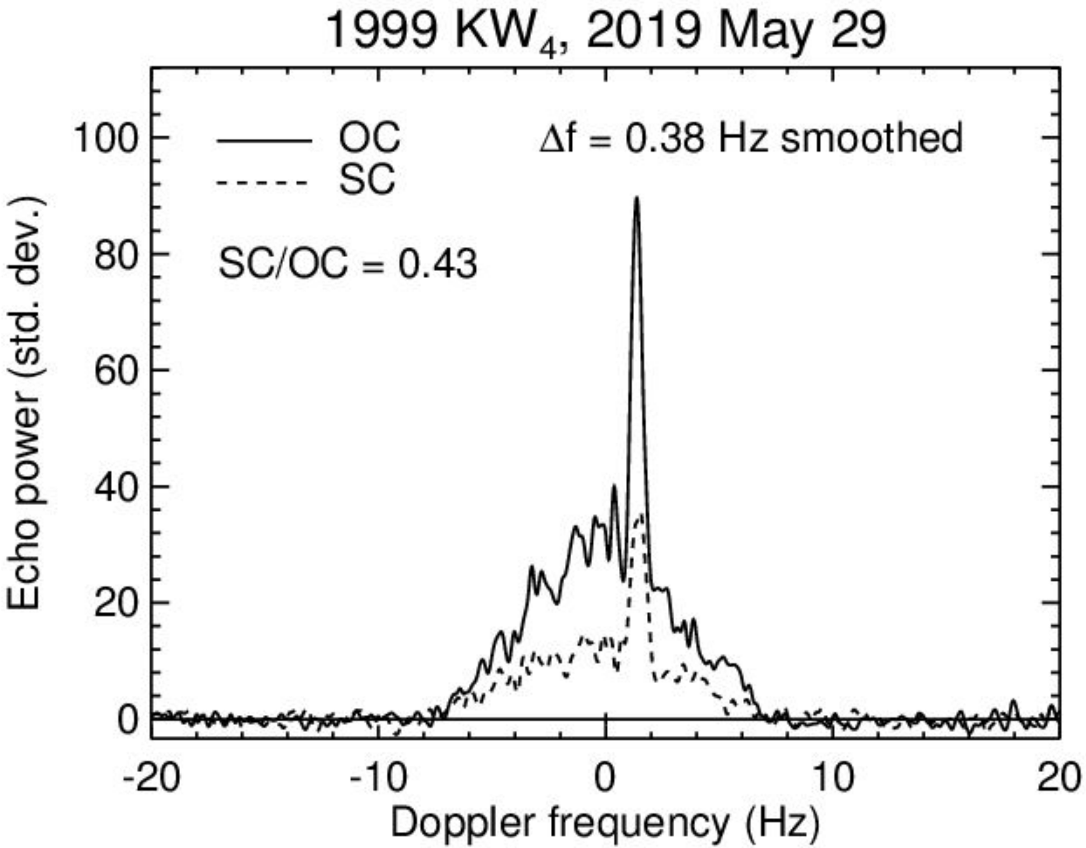
More Plots!

- A binary asteroid! You can see the shapes of two distinct signals in this plot
- If you observe a binary over too short a period, you might not see the spike because the secondary might be out of sight for the observation
- Most binaries are confirmed using radar!



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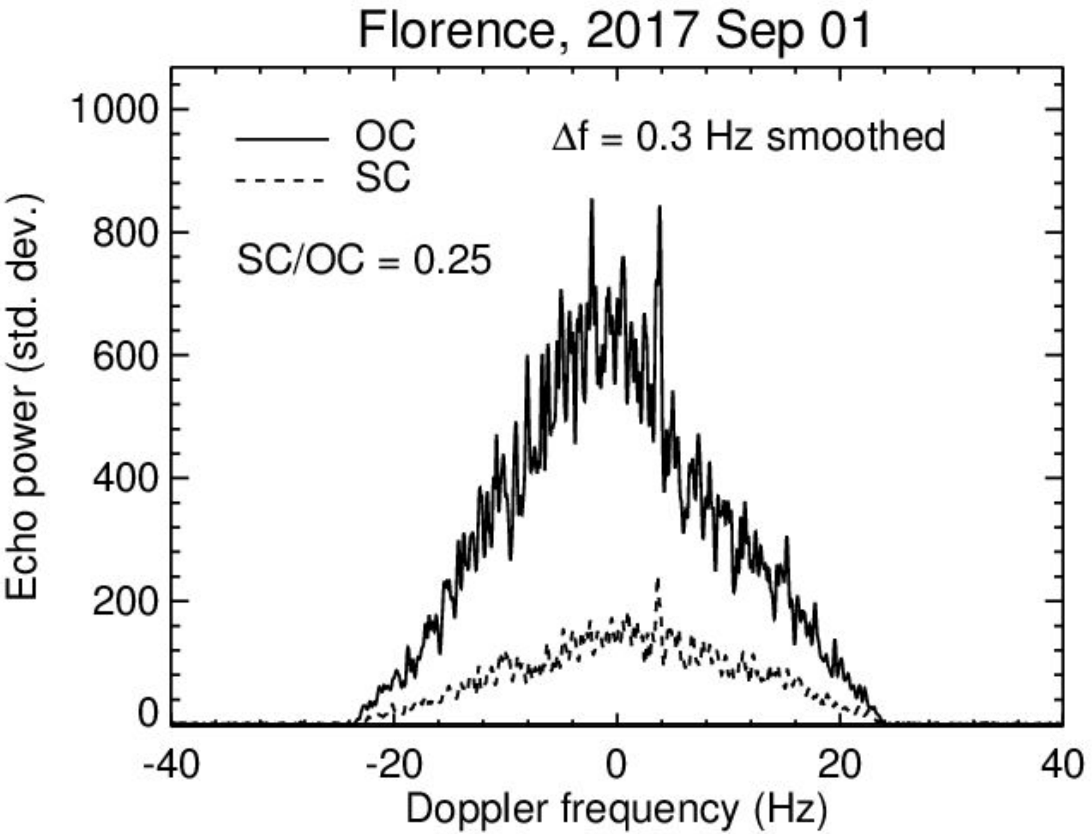
More Plots!

- This one is a very interesting case, this is a large asteroid with two smaller moons - a triple system!
- Spike on right in both OC and SC that indicates the detection is really a binary
- Sometimes the binary is not obvious



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Delay Doppler Signals I

- Binary Phase Coded (BPC) Data
  - The data is coded in such a way that the return signal can tell us more information about the target - such as ranging information, another important factor in getting a good ephemeris for a target
  - The transmitted signal phase can be changed by 180 degrees every **baud,** or time interval (the size of which determines the range resolution)
  - Signal flips are sent in a pseudo-random repeating pattern in such a way that within one cycle of the code the signal is unique - the length of this cycle is the **codelength**, which determines the total range the signal can distinguish

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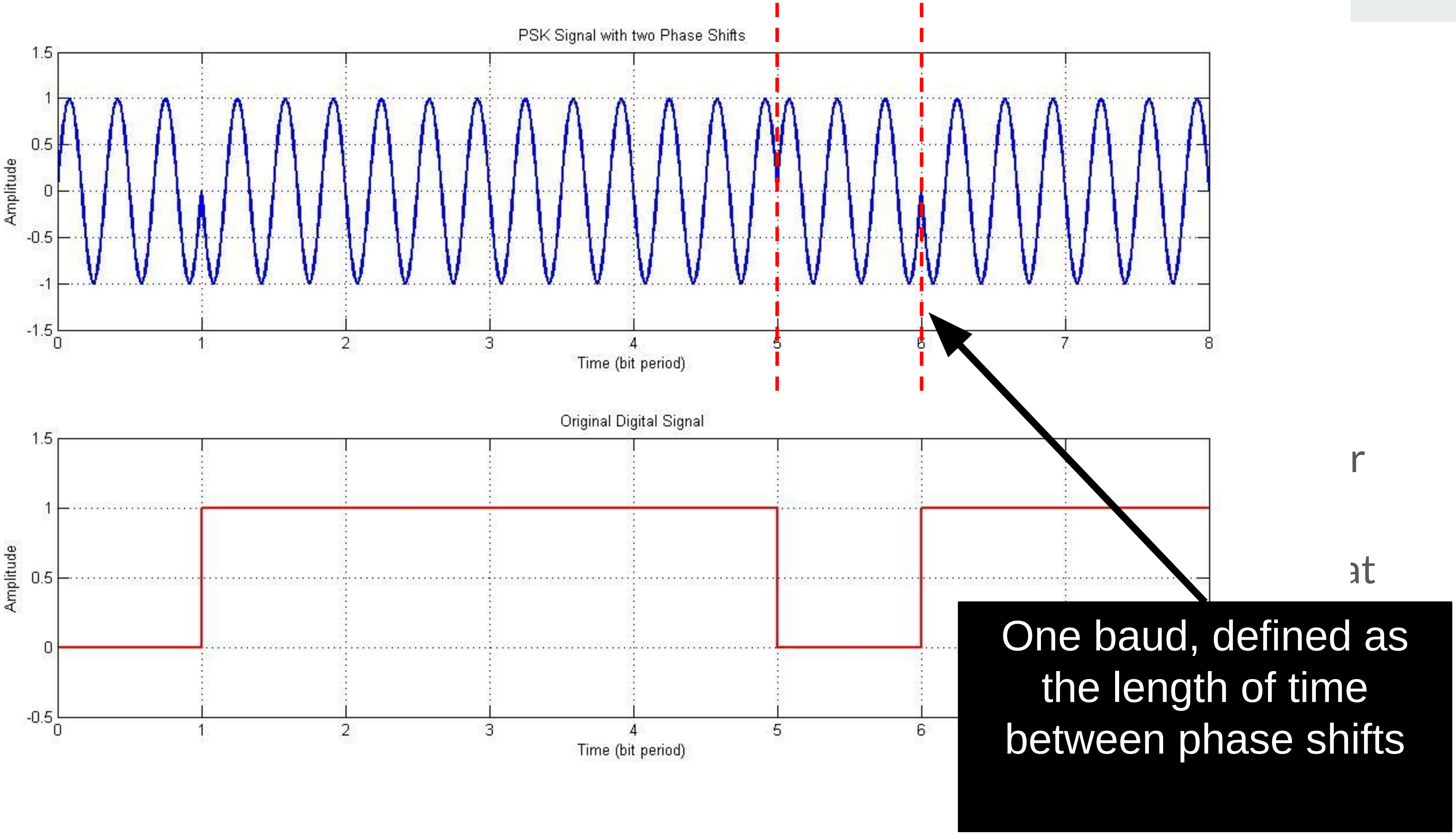

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Delay Doppler Signals II

- Binary Phase Coded (BPC) Data
  - For example, a codelength of 7 with a 4 microsecond baud would represent a delay resolution of 4 microsec, or range resolution of (300*10^6 m/s) * (4*10^-6 s) / 2 = 600 m, and a total range that can be decoded of (600 m * 7) = 4200 m - the length at which the code repeats
  - Can also sample each delay (range) bin multiple times, **samples per baud**
    - The resulting data will have a higher snr but also have correlation of values in range dimension, and will need to be decoded

Delay Doppler Signals III

- Determining observation specifications
    - GIO for semi-course imaging
        - If SNR < 20 as it will likely be too weak for finer resolutions
        - If target is > 5 km in diameter
    - PFS for fine resolution
        - Needs high SNR, better if under 5 km in diameter
    - Shorter baud length - meaning finer frequency resolution - will increase the number of pixels that the return signal is being divided across, which makes each pixel fainter. So a longer baud means a less well resolved but stronger image

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Visualization

Time Delay: Distance

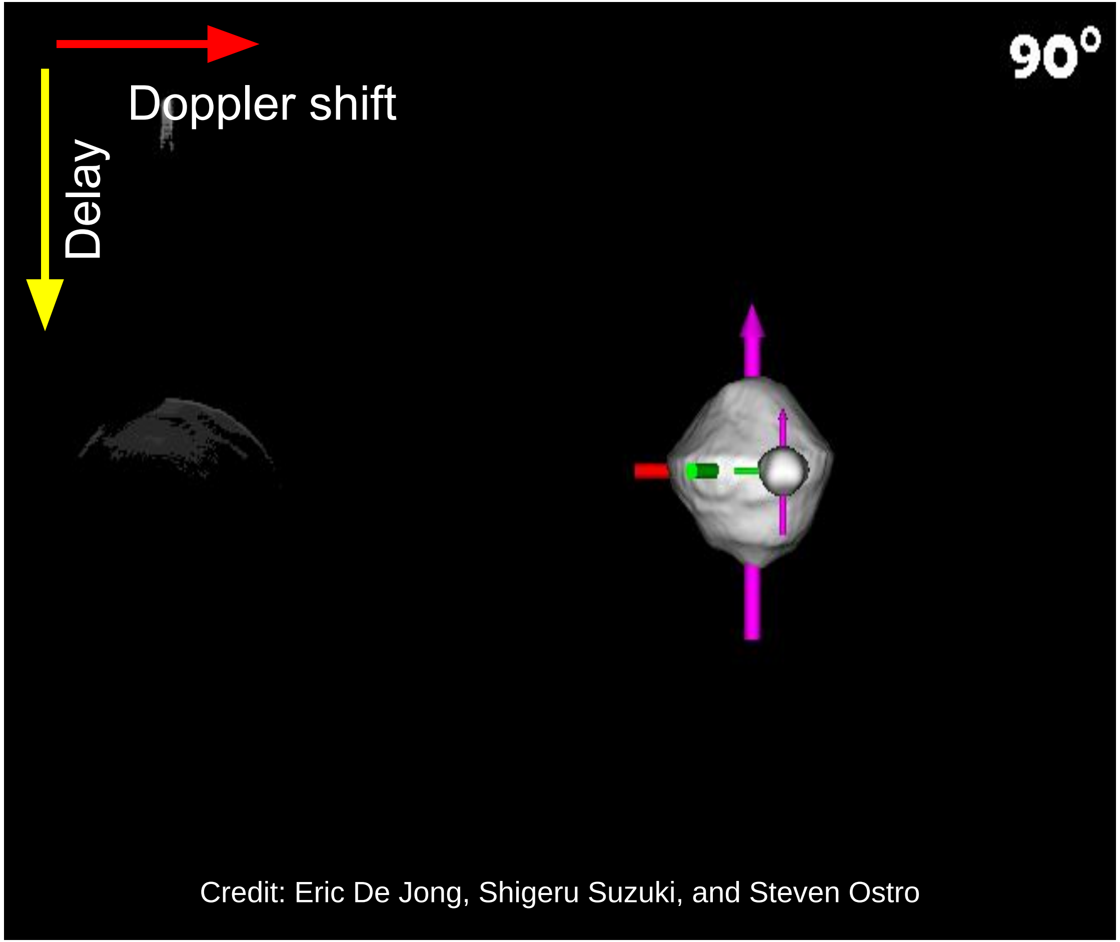
- Vertical axis
- Increasing downward
- Points at the top are closest to the observer

Doppler Frequency: Velocity

- Horizontal axis
- Increasing to the right
- Points on the right are approaching the observer

Splitting signal into discrete range & frequency bins

Requires high SNR



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

Data Processing: GIO I

- After downloading the data into its directory for processing, we create a DRV file for it
  - This file contains a list of parameters that will be used to create all other files during the processing, such as the codelength, the bin numbers we want to keep (keeping less speeds up processing), the fft length to use (determines frequency resolution of output images), etc.
- The frequency resolution of output image= 1/(baud*codelength*spcfftlen)
  - Spcfftlen can increase the resolution on the final image, but that divides the signal into more bins
  - Shorter bauds take longer to process
  - understanding what balance of frequency resolution you want vs processing time vs signal strength is important!

Data Processing: GIO II

Here is an example of what our drv file could contain:

```
fbase     BASENAME
tapedev   DATAFILE
codelen       8191  # Code length
bits             4
numpol           1  # Number of polarizations available
poltouse         1    # Polarization; 1 = OC only; 2 = SC (or both)
bin1             1  # First delay bin of code to keep in the image
numbins       8191  # Number of rows to keep after bin1
smpperbaud       1    # Samples per baud
machine         ri    # Choices are: ri,cbr,pfs,bytes,floats
dcdpacked        0    # 0, or 1,2,4 samples/32bit word
dcdfftlen    32768
nthreads 4
codestodecode 99999999
removedc         1    # Remove dc prior to decoding
cohavg           0
spcfftlen       32     # freq res would be about 0.95 Hz for a bandwidth of 30.5 Hz
spcfftkeep      32     # Save this number of freqs around center
codetype     aopnc
xoff             0
#tmsmp         2e-6   # This only matters if x offset != 0
```

$$code\ BW = \frac{1}{baud * codelength} = \frac{1}{4*10^{-6}*8191} \approx 30.5\ Hz$$

$$Freq\ Res = \frac{BW}{spcfftlen} = \frac{1}{4*10^{-6}*8191*32} \approx 0.95\ Hz$$

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Data Processing: GIO III

- After editing the DRV file, we use it to create raw files from each scan
  - Some with header info some binary data files
- We then decode and fourier transform each scan
- Then generate a preliminary image to determine what, if any, further processing is needed
- Then we sum the images together
- Then we open the image using ds9, and look for the image of the target. We have a couple programs designed to help identify the target if it is faint or only in one pixel

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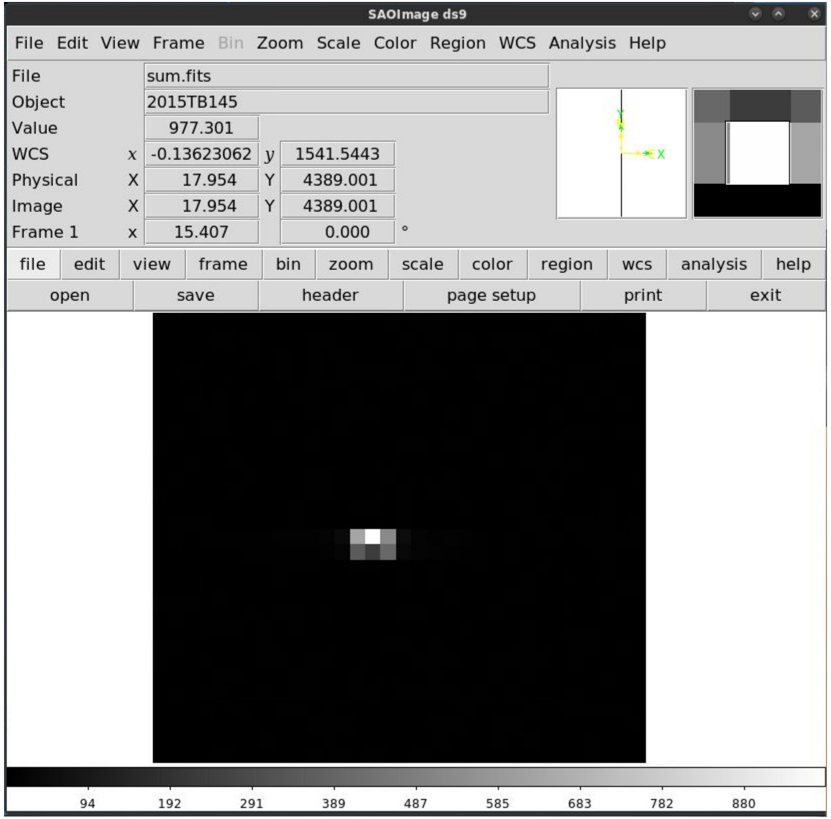
Data Processing: GIO IV

- This is an image made using 4 microsecond data
- For coarser resolution, the resulting image is often only a few pixels (or even just one pixel!) and looks like the image shown
- For finer resolution, we do a similar process using PFS data



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Data Processing: PFS I

- PFS data is typically recorded at 20MHz (1 sample every 0.05 us)
- For a baud length of 0.05 us this means we take one sample per baud, for a baud length of 0.10 us would be two samples per baud, etc.
- A baud length of 0.05 us would therefore have up to 65,535 delay bins (the codelength), with the expected signal found around bin 30,000 (roughly half), and a baud length of 0.10 us would have up to 131,070 delay bins, with the expected signal location around bin 60,000
- The expected bin would be where the signal is if the ephemeris is perfect, and typically for imaging like this we know the ephemeris fairly accurately
- The row the signal is found in tells us the distance to it

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Data Processing: PFS II

```
fbase     2015TB145       # target name or designation
tapedev   /share/aeron5/SN12.001
codelen       65535 # codelength
bits              2
numpol            2 # number of polarizations available
poltouse          1     # polarization; 1 = OC only; 2 = SC (or both)
bin1          30110 # first bin of code to keep in the image
numbins         200 # for PFS you usually want to start by keeping at least 2000 bins around the center
smpperbaud        1     # samples per baud
machine         pfs     # choices are: ri,cbr,pfs,bytes,floats
dcdpacked         0     # 0, or 1,2,4 samples/32bit word
dcdfftlen   262144
numthreads   1
codestodecode 99999999
removedc          1     # remove dc prior to decoding
cohavg            1
spcfftlen      2436     # freq res about 0.13 Hz for a bandwidth of 305 Hz
spcfftkeep      200     # save # frq bins about dec
codetype      aopnc
xoff              0
#tmsmp          5e-8    # This only matters if x offset != 0
```

$$code\ BW = \frac{1}{baud*codelength} = \frac{1}{0.05*10^{-6}*65535} \approx 305\ Hz$$

$$Freq\ Res = \frac{BW}{spcfftlen} = \frac{1}{0.05*10^{-6}*65535*2436} \approx 0.13\ Hz$$

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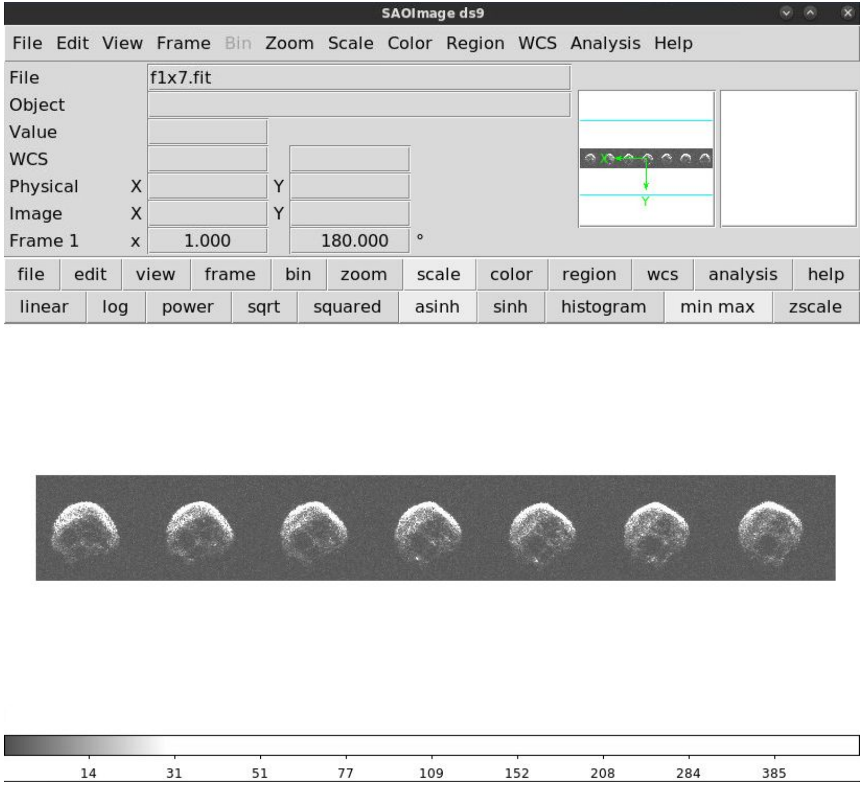
Data Processing: PFS III

- This process is basically the same as with GIO data, as is the process:
- After creating the DRV file from a template we use for the specific PFS data we took, we use the DRV file as we did with the GIO data to create raw and header files from each scan
- Then, just like with GIO, we decode and Fourier transform on the data to create initial images
- Sum the images, open in ds9



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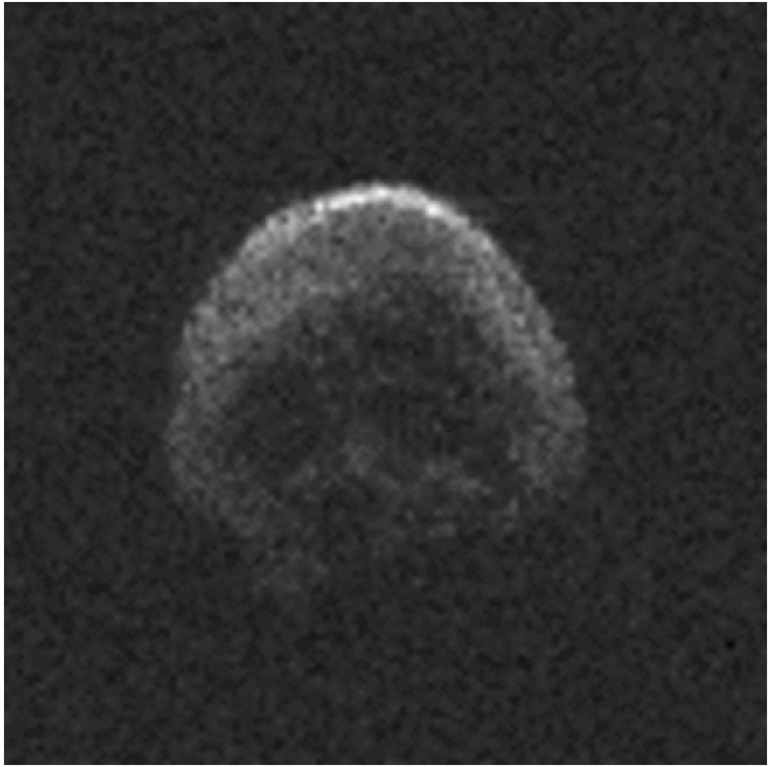
Final FITS Files

- Use a shell script to compile FITS to make a final image
- After finishing the initial FITS for either GIO data or PFS data, we can generate final FITS files as well as animations, if we can see the target has rotated during the course of the observation and there is enough data to do so



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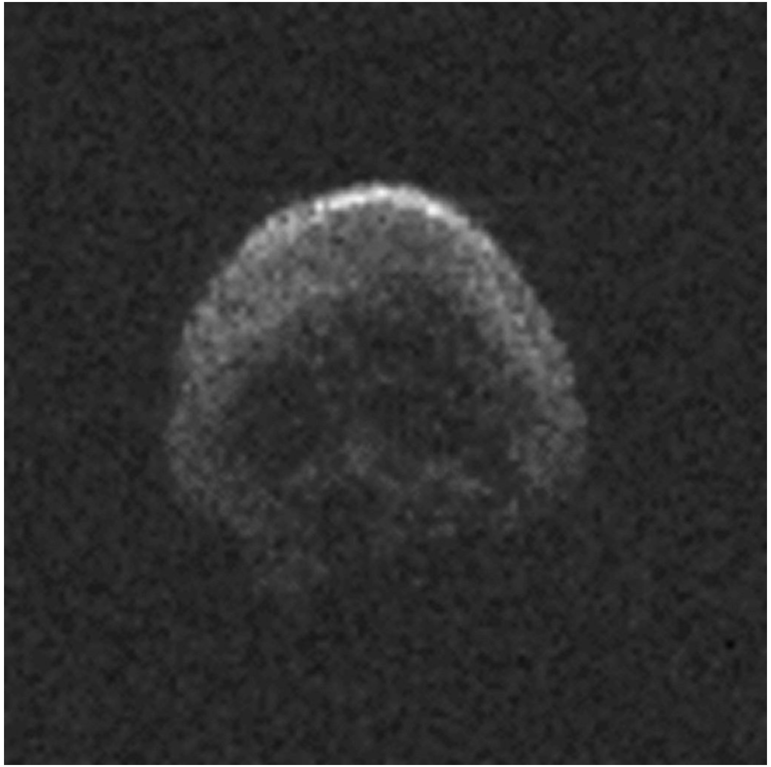

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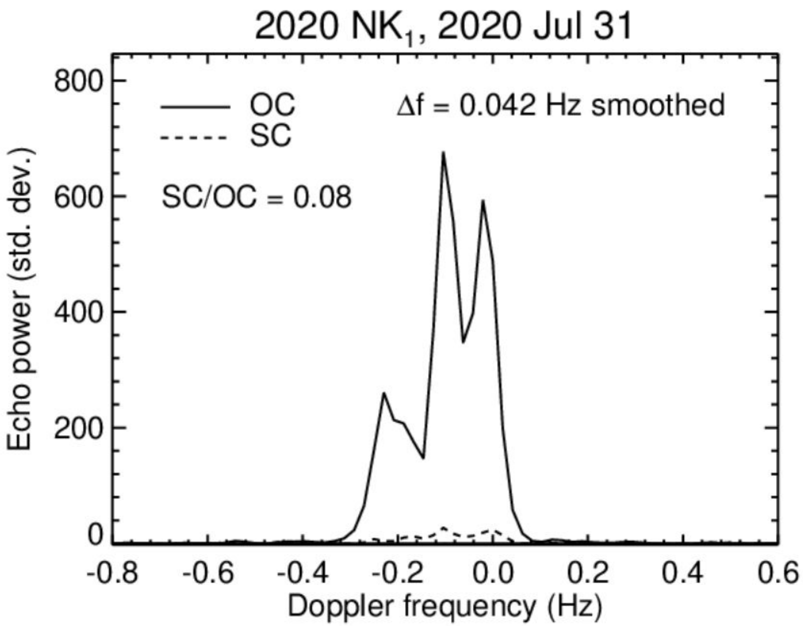
What does this tell us?

- Higher quality astrometry, ranging information - Example:
  - 2nd to last observation done at the Arecibo Observatory: 2020 NK1
  - Before observations/data analysis at AO, this was flagged as a high priority PHA
  - After observations at AO - giving 2 new doppler measurements and a delay doppler measurement - the uncertainty in its predicted location went down drastically
    - orbit predictability window went from 1 year to almost 600 years
  - Eliminated the possibility of it hitting the Earth in the next century



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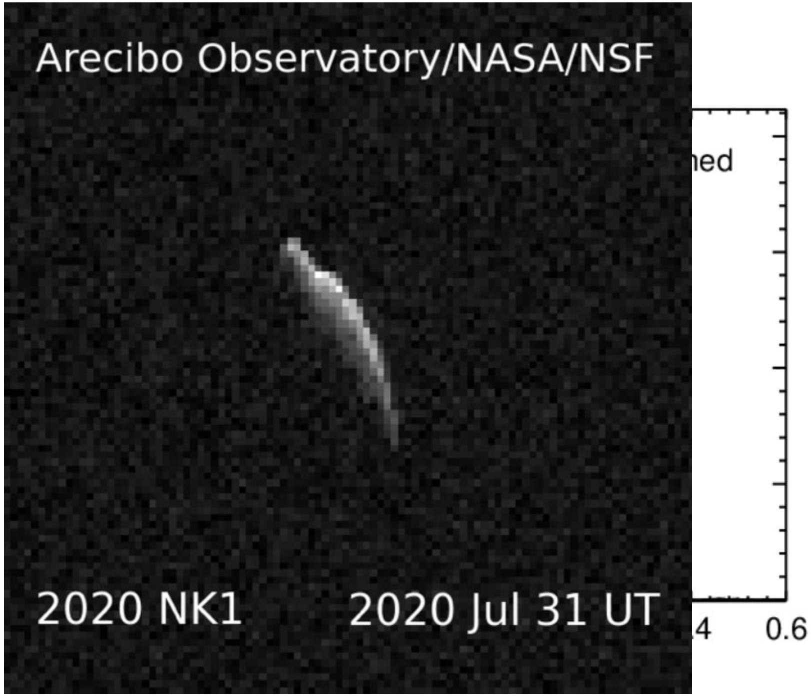

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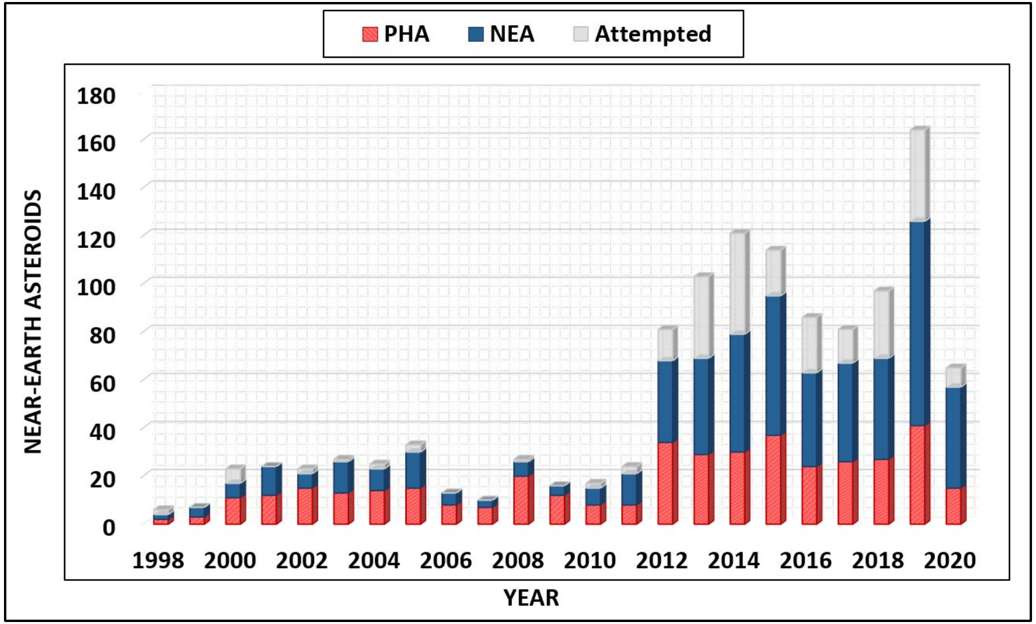
What does this tell us?

- Higher quality astrometry, ranging information
- Shape modelling applications
- Better understanding of characteristics of different types of asteroids
- Knowing these properties can help plan space missions
- There are many new asteroids discovered each year, and planetary radar is instrumental in getting accurate orbit predictions in only a few observations - all this data processing has the end goal of helping improve these predictions



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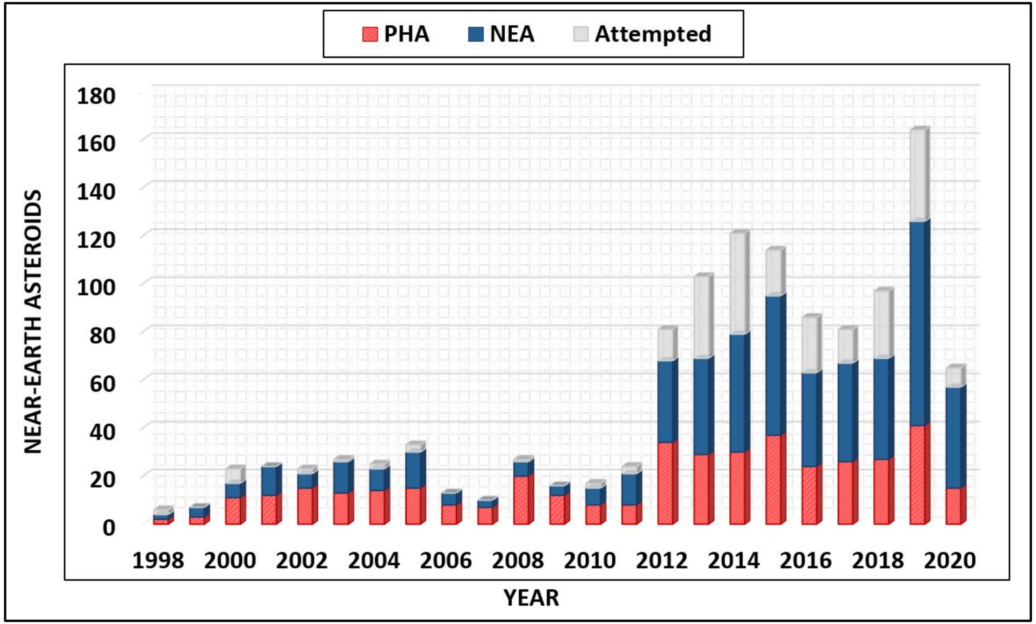
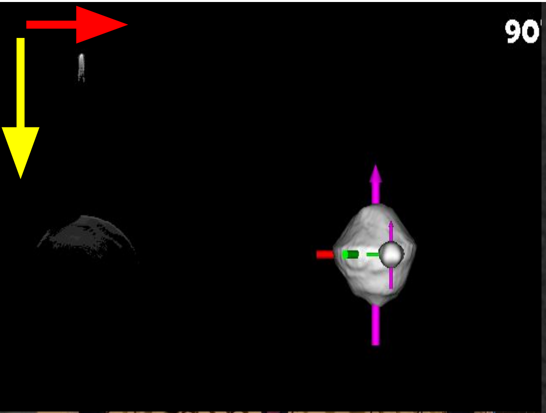
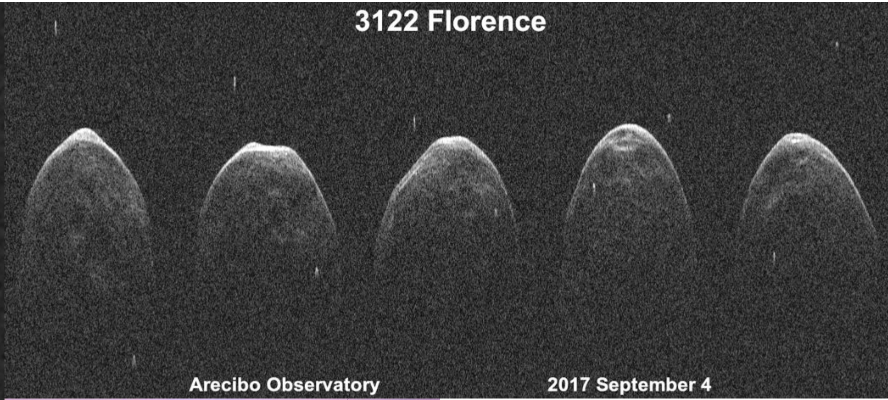
Questions?

Thank you!!




90'


Arecibo Observatory/NASA/NSF
2020 NK1
2020 Jul 31 UT


3122 Florence
Arecibo Observatory
2017 September 4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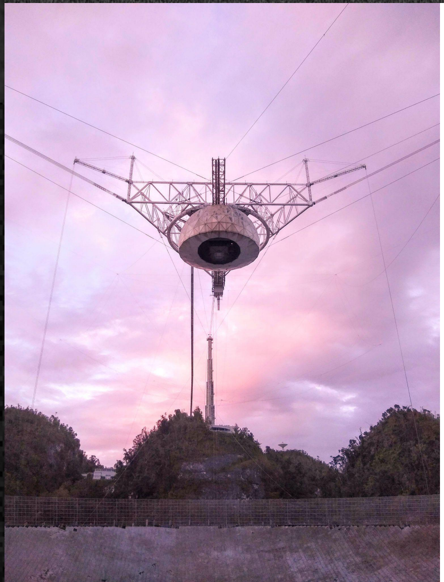
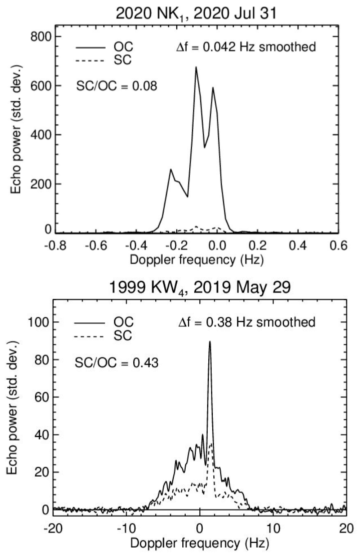
PUERTO RICO




2020 NK_1, 2020 Jul 31
OC
SC
Δf = 0.042 Hz smoothed
SC/OC = 0.08
Echo power (std. dev.)
Doppler frequency (Hz)
1999 KW_4, 2019 May 29
OC
SC
Δf = 0.38 Hz smoothed
SC/OC = 0.43
Echo power (std. dev.)
Doppler frequency (Hz)