Doppler Shift from Earth-Orbiting Satellites

HAMSci 2019

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Doppler Shift

- The change in the observed frequency of a wave-like signal when there is relative motion between the source and the observer.

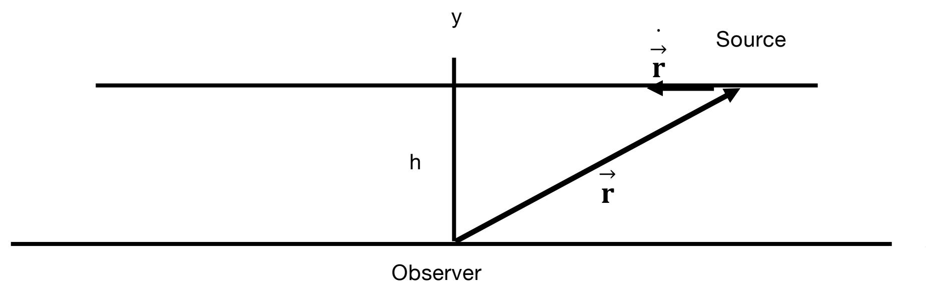
$$f_O = \frac{c f_S}{c + v}$$

DOPPLER SHIFT IN THE ACOUSTIC REGIME

$$\vec{\mathbf{r}} = -v(t - t0)\,\vec{\mathbf{i}} + h\,\vec{\mathbf{j}}$$

$$\dot{\vec{\mathbf{r}}} = \frac{d}{dt}(-v(t - t0))\,\vec{\mathbf{i}} + \frac{d}{dt}h\,\vec{\mathbf{j}} = -v\,\vec{\mathbf{i}}$$

$$\frac{\dot{\vec{\mathbf{r}}} \cdot \vec{\mathbf{r}}}{|\vec{\mathbf{r}}|} = \frac{v^2(t - t0)}{\sqrt{v^2(t - t0)^2 + h^2}}$$



- Assumptions
  - Fixed source frequency, f_S
  - Moving along a straight path some distance, h, from the observer
  - Constant speed, v_S

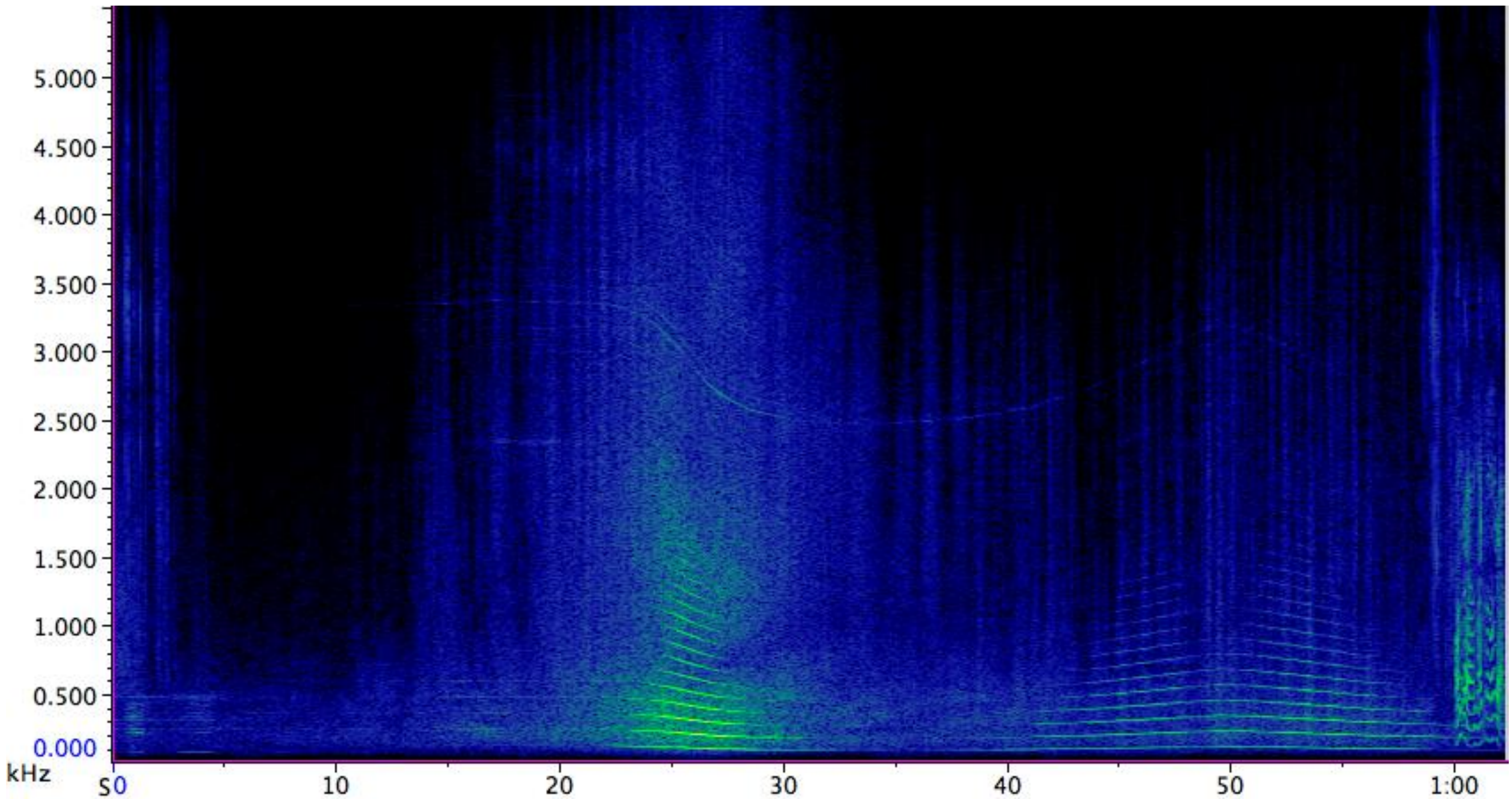
The Model

$$f_O = \frac{c f_S}{c + \dfrac{v_S^2 (t - t_0)}{\sqrt{v_S^2 (t - t_0)^2 + h^2}}}$$

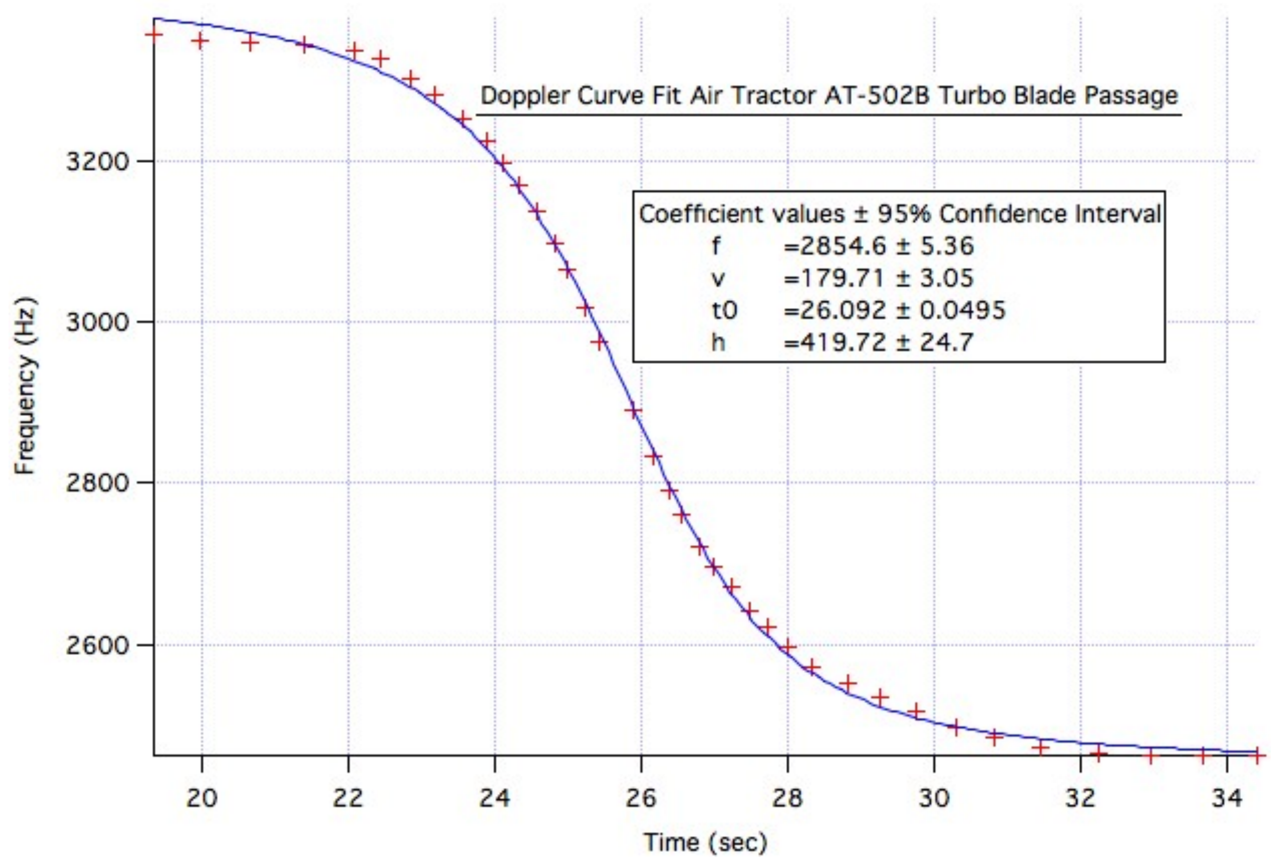
where
f_O, the observed frequency
c, the speed of sound
f_S, frequency of the source
t_0, time of closest approach
h, distance of closest approach
v_S, speed of source

- An expression for the observed frequency as a function of time.
- The equation can be fit to a set of time and frequency data by adjusting the four parameters using a curve fitter based on the Levenberg-Marquardt method.
- Once the speed, and time and distance of closest approach are in hand the distance between source, moving along the assumed path, and observer can be estimated at other times.

AT-502B Air Tractor



AT-502B Air Tractor



TG 328
December 19, 1958
Copy No.

A SIMPLIFIED DOPPLER NAVIGATING SYSTEM

by

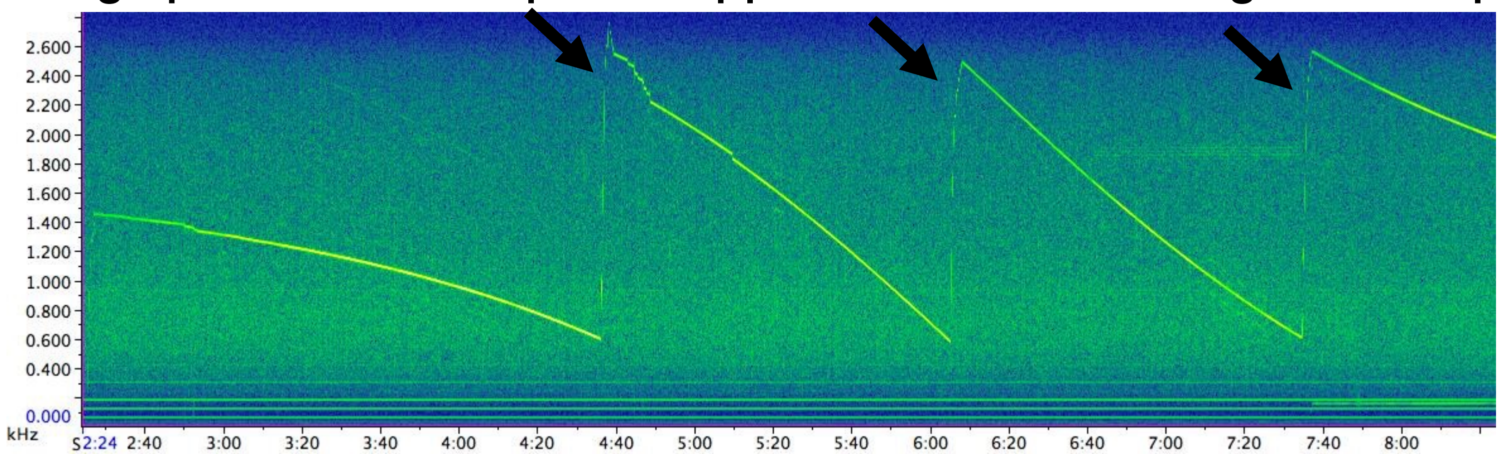
William H. Guier

Application to Earth-Orbiting Satellites

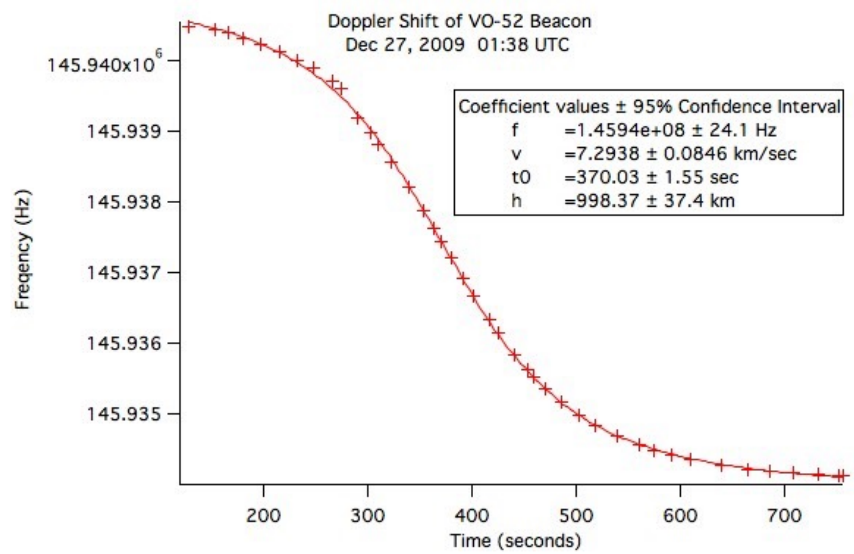
- Around Christmas 2009
- Kenwood TS-700 S 2-meter all mode transceiver
- Four-element, 2-meter Yagi antenna
- One or two MacBook computers
- Software: Raven-Lite, Audacity, IGOR-Pro, Predict

HAMSAT, VO-52

Re-tuning operations to keep the Doppler-shifted beacon signal in the passband.

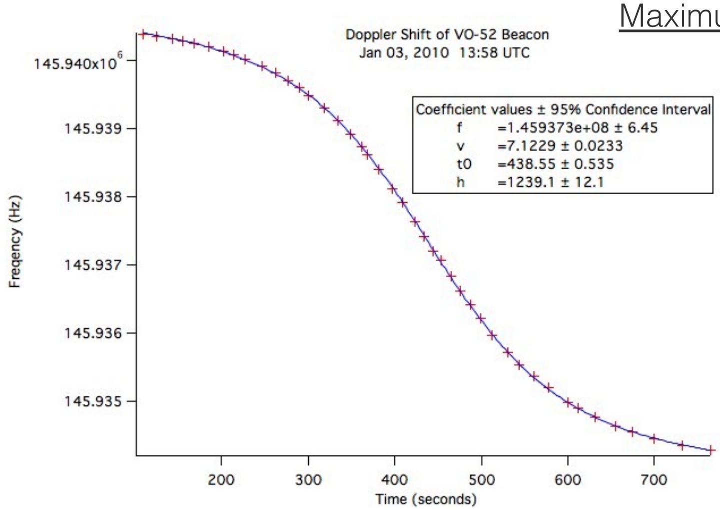


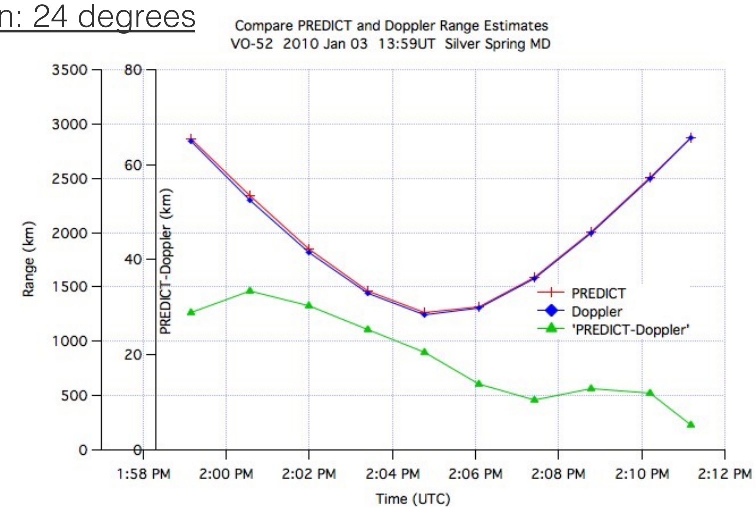
- To apply the model to satellite radio beacons requires only changing the speed of sound to the speed of light.
- We continue to use the straight line path as an approximation to the segment of the curved orbit.
- We chose HAMSAT (VO-52, now decommissioned) having a 145.936 MHz unmodulated carrier for out first tests.



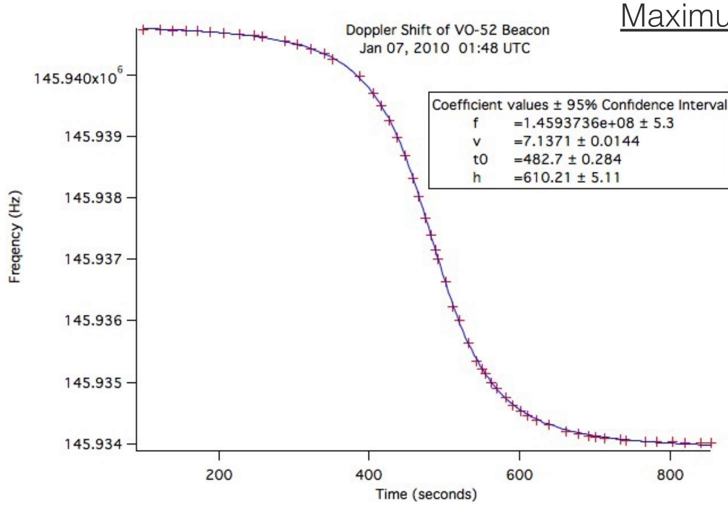
Compare Doppler Slant Range with PREDICT

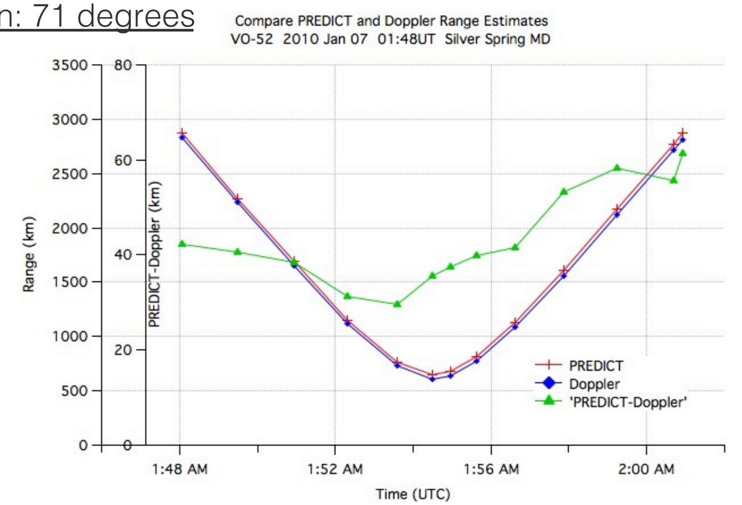
Maximum Elevation: 24 degrees





Maximum elevation: 71 degrees

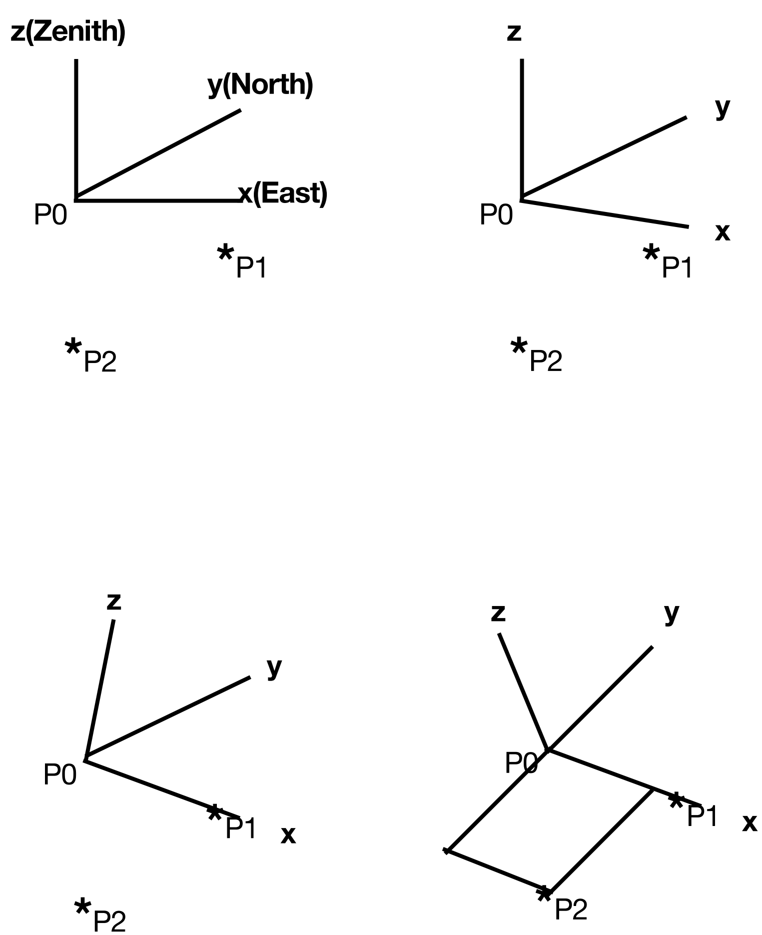




Estimating the Ground Track

- Given the slant ranges from three widely separated ground stations, find the satellite locations and plot the ground track
- To develop the method, I use datasets derived from PREDICT pass predictions
- The method I develop uses trilateration, solving a system of equations describing three spheres.

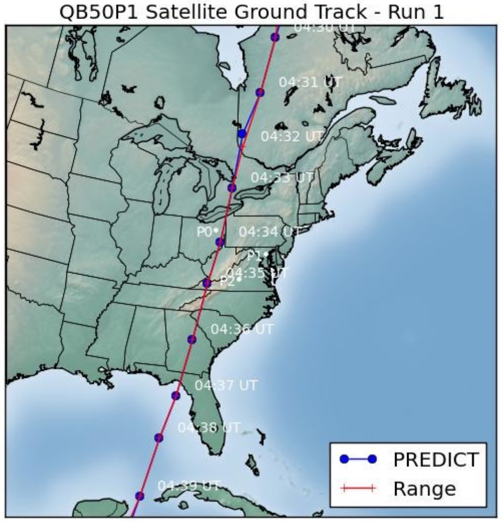
Trilateration



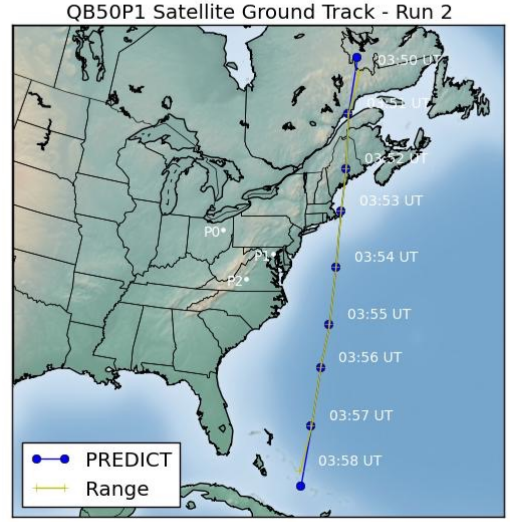
- Start with alti-azmuthal coordinate system with origin at P0
- Rotate around z
- Rotate around new y
- Rotate around new x
- All centers are in the plane z=0
- Solve system of three spheres at each time of interest.
- When done, do the rotations in the reverse order back to original coordinate system

Ground Track Results

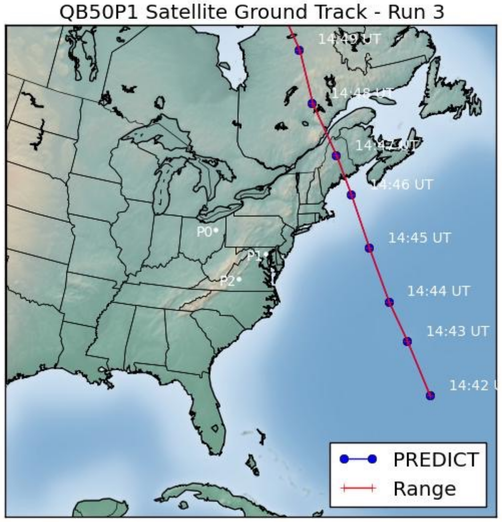
QB50P1 Satellite Ground Track - Run 1



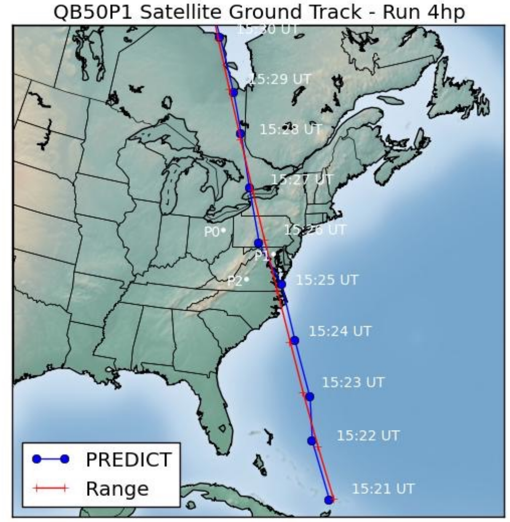
QB50P1 Satellite Ground Track - Run 2



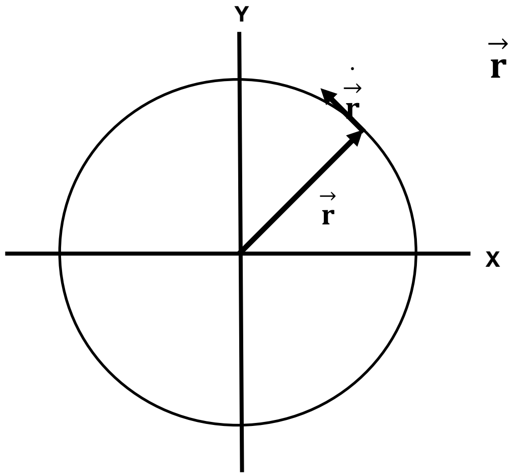
QB50P1 Satellite Ground Track - Run 3



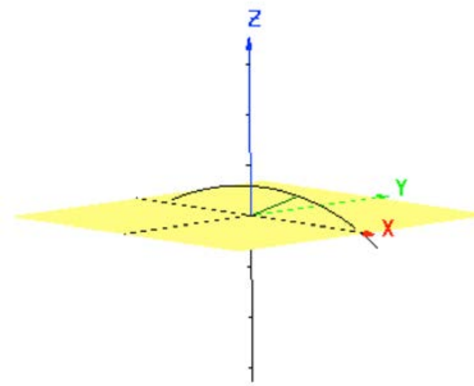
QB50P1 Satellite Ground Track - Run 4hp



Circular Orbit Model



$$\vec{\mathbf{r}} = (R_E + alt)\cos\left(\frac{v(t - t0)}{(R_E + alt)}\right)\vec{\mathbf{i}} + (R_E + alt)\sin\left(\frac{v(t - t0)}{(R_E + alt)}\right)\vec{\mathbf{j}}$$



- Tilt orbital system around x-axis to some arbitrary angle so orbit is off-zenith
- Rotate coordinate system about x-axis to point z-axis toward observer on the surface
- Translate the coordinate system along the z-axis to the surface.

Then in new system find:

$$\vec{\mathbf{r}}, \dot{\vec{\mathbf{r}}}, and \frac{\dot{\vec{\mathbf{r}}} \cdot \vec{\mathbf{r}}}{|\vec{\mathbf{r}}|}$$

Where does this go next?

- HAMSAT/VO52 observations were a fun kludge:
  - Kenwood TS-700S with ~3 kHz SSB bandwidth.
  - Sound card recorder (Audacity) and a handful of stand-alone analysis tools (RAVEN-lite, IGOR-pro, and probably some MATLAB and Excel).
  - HAMSAT/VO52 is dead now almost a decade later.
- But, we live in the future!
  - ”RTL-SDR” devices are cheap, easy to use.
  - Open-source Python tools exist for all aspects of this work.
  - There are more suitable spacecraft (e.g., CAS-3/XW-2 series) broadcasting in the 2m band.

Experimental Setup

```
ibiza:~$ rtl_sdr -S -f 145.790e6 -s 252000 -g 0 XW2C_20190226_120030.bin
Found 1 device(s):
  0:  Generic, RTL2832U, SN: 77771111153705700

Using device 0: Generic RTL2832U
Found Rafael Micro R820T tuner
Exact sample rate is: 252000.000300 Hz
[R82XX] PLL not locked!
Sampling at 252000 S/s.
Tuned to 145790000 Hz.
Tuner gain set to automatic.
Reading samples in sync mode...
```

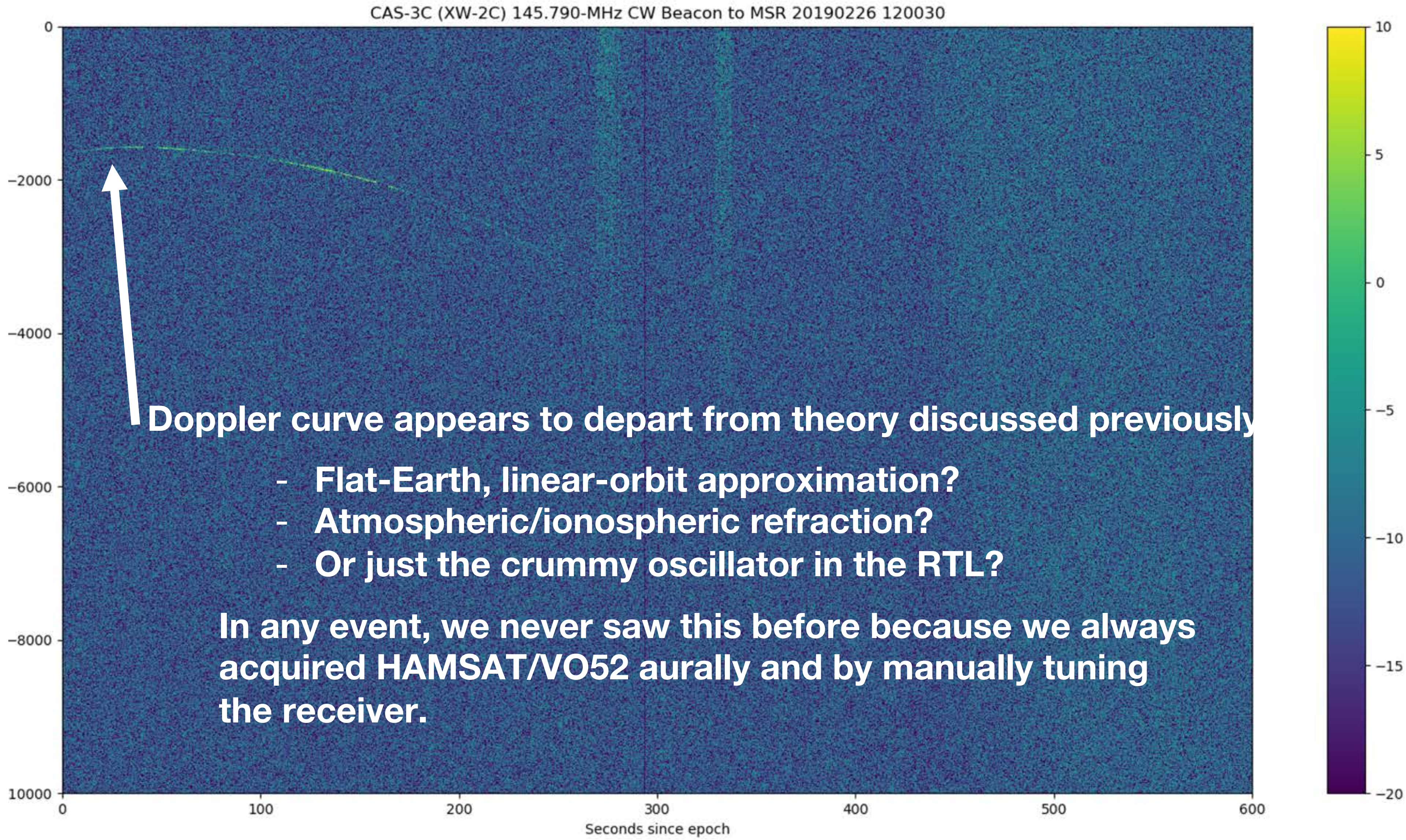

Skyfield

SciPy.org

NumPy

matplotlib

So, we tried it and saw something unexpected

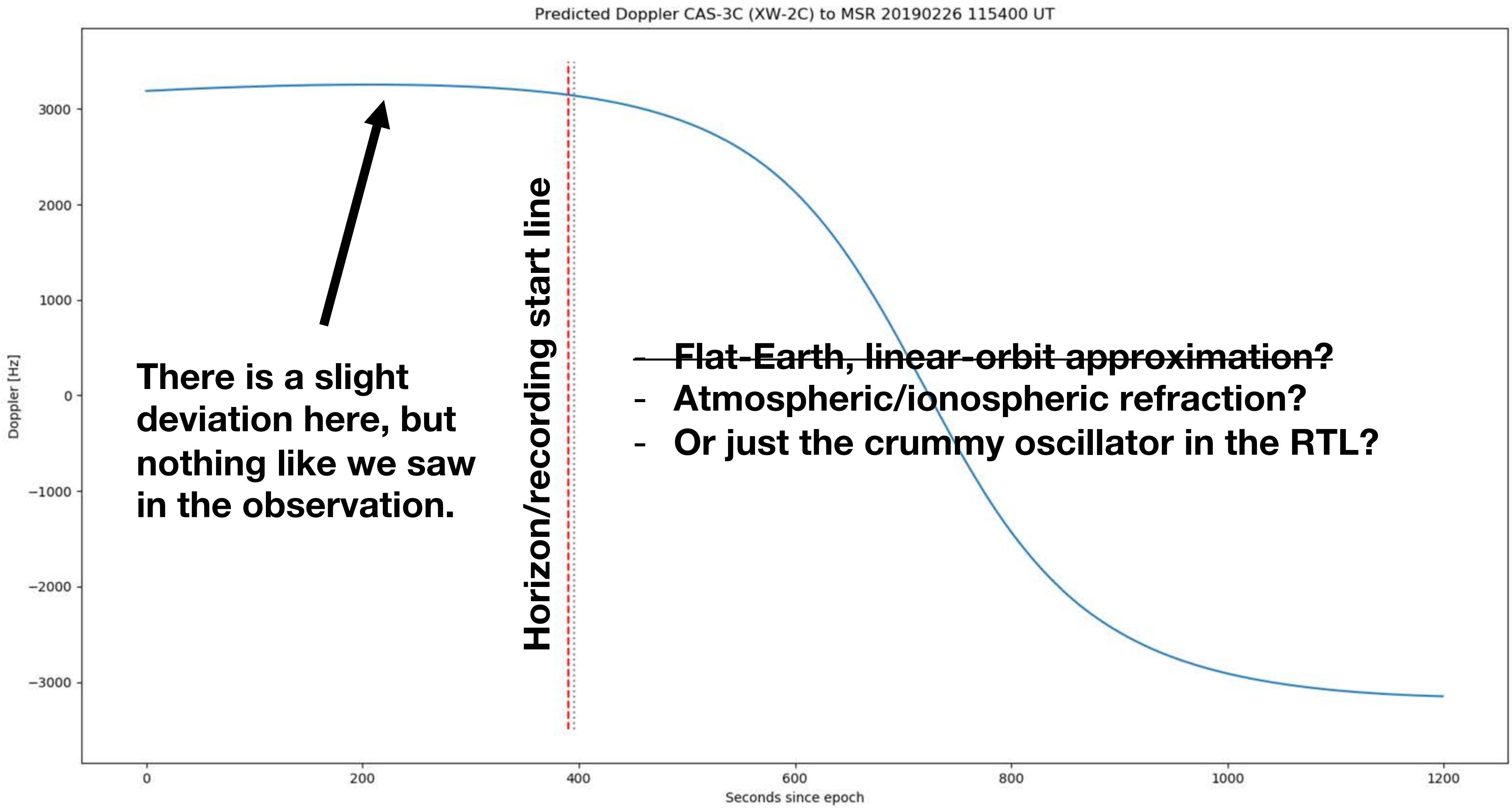


Doppler curve appears to depart from theory discussed previously

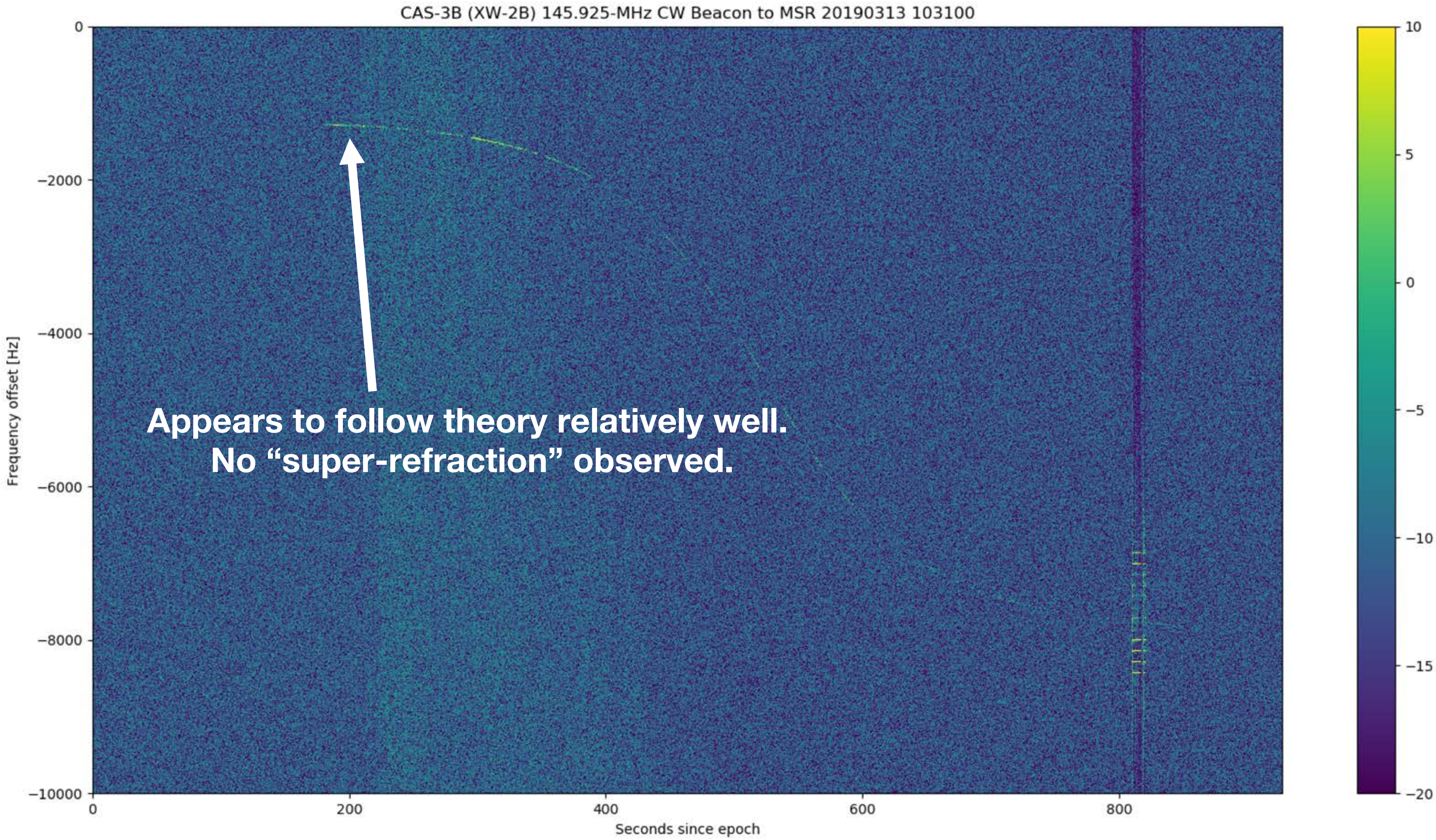
- Flat-Earth, linear-orbit approximation?
- Atmospheric/ionospheric refraction?
- Or just the crummy oscillator in the RTL?

In any event, we never saw this before because we always acquired HAMSAT/VO52 aurally and by manually tuning the receiver.

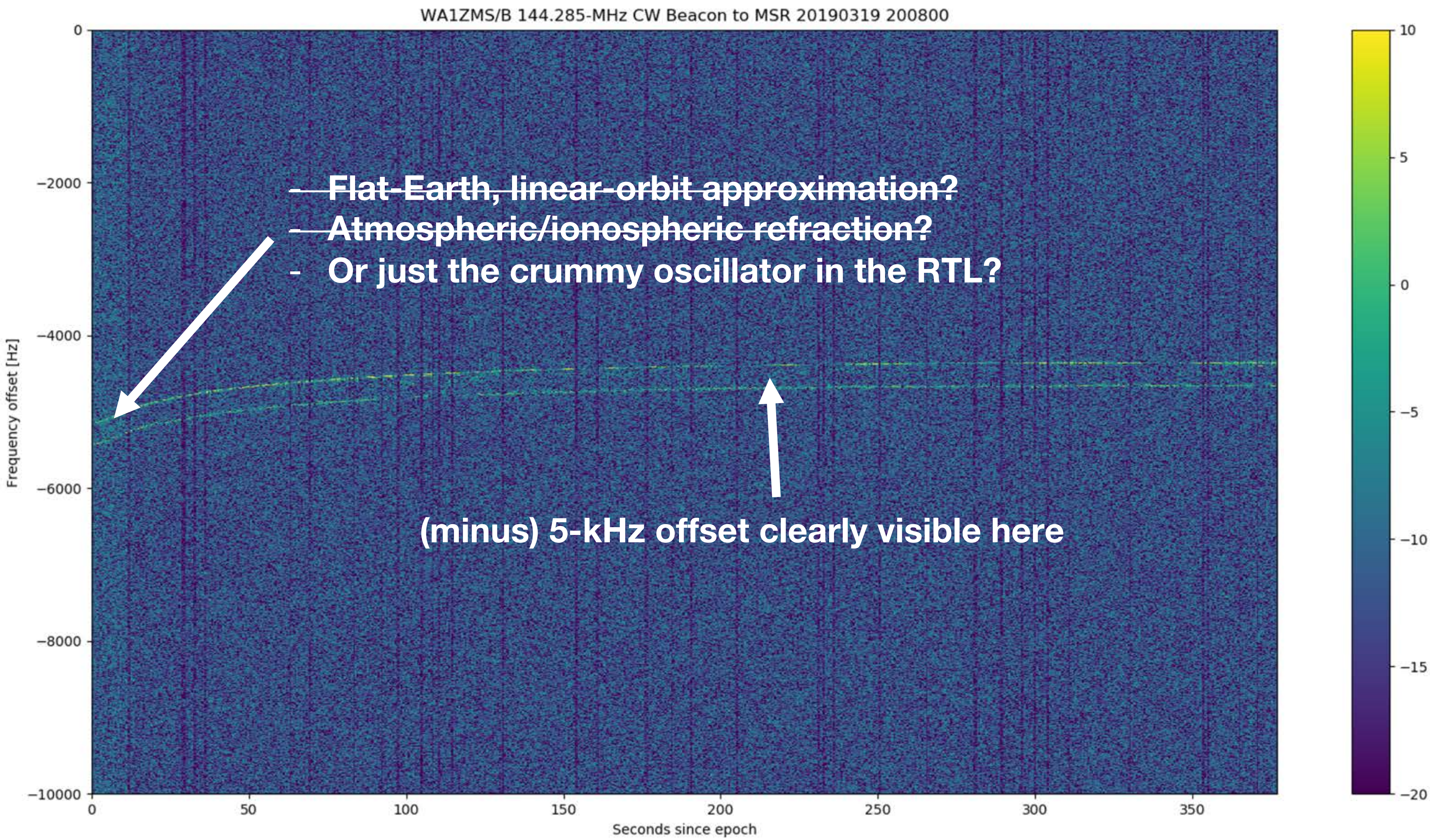
Predicted Doppler for the CAS-3C (XW-2C) orbit



Start Recording Before Satellite Rises



GPS-disciplined beacon



Discussion

- From the pulpit:
  - Observation of physical phenomena are within the capabilities of hams on relatively tight budgets, and without access to fancy tools/software.
  - Be curious: Investigate anomalies you observe.
- There are "advanced" techniques we should be able to use to monitor satellite beacons and derive ionospheric data. This is beyond the scope of this talk. Maybe next year?
- We will bundle up some Python analysis tools.