Communicating with a space probe using Software Defined Radio:

The ISEE-3 Reboot Project

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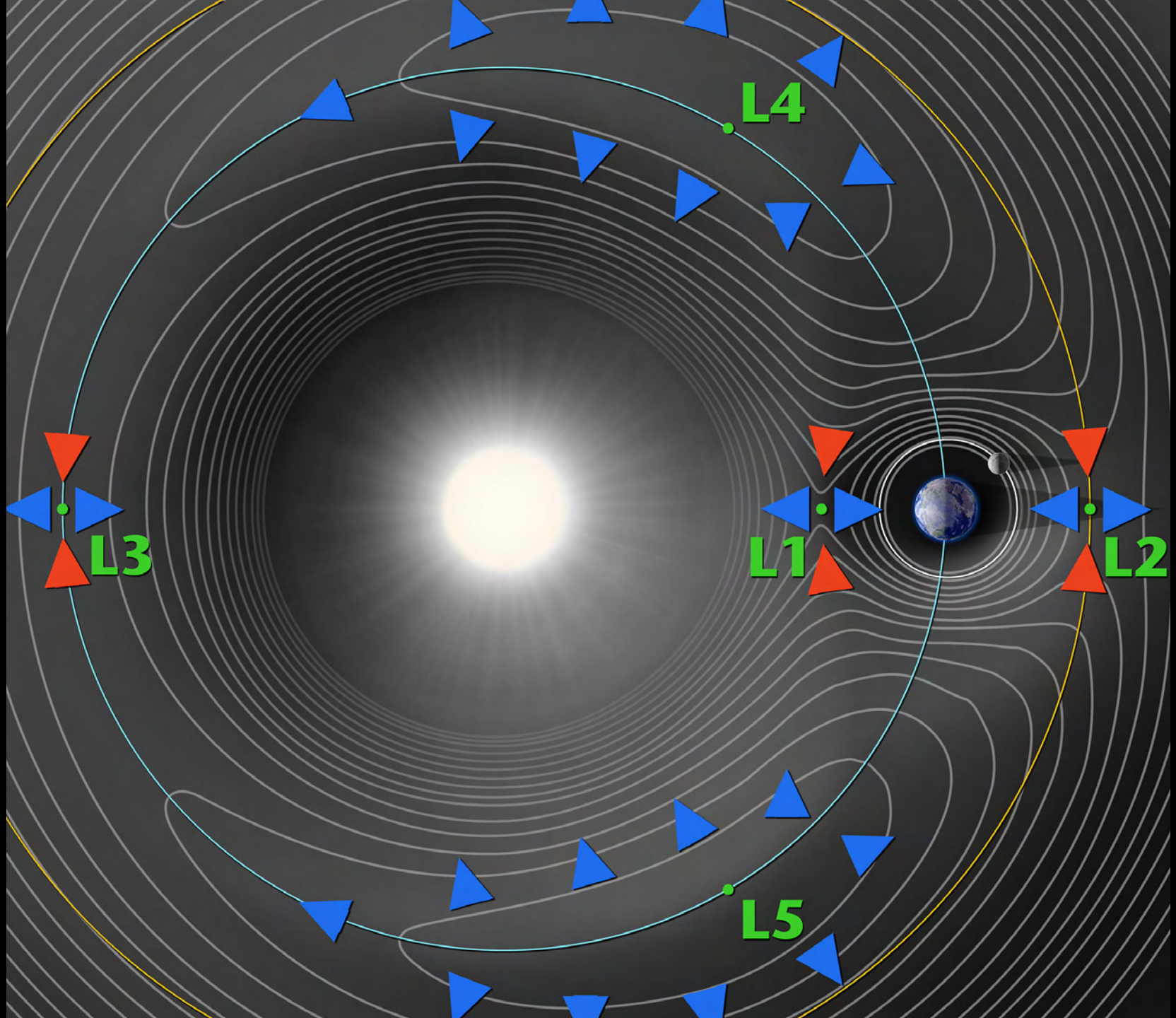
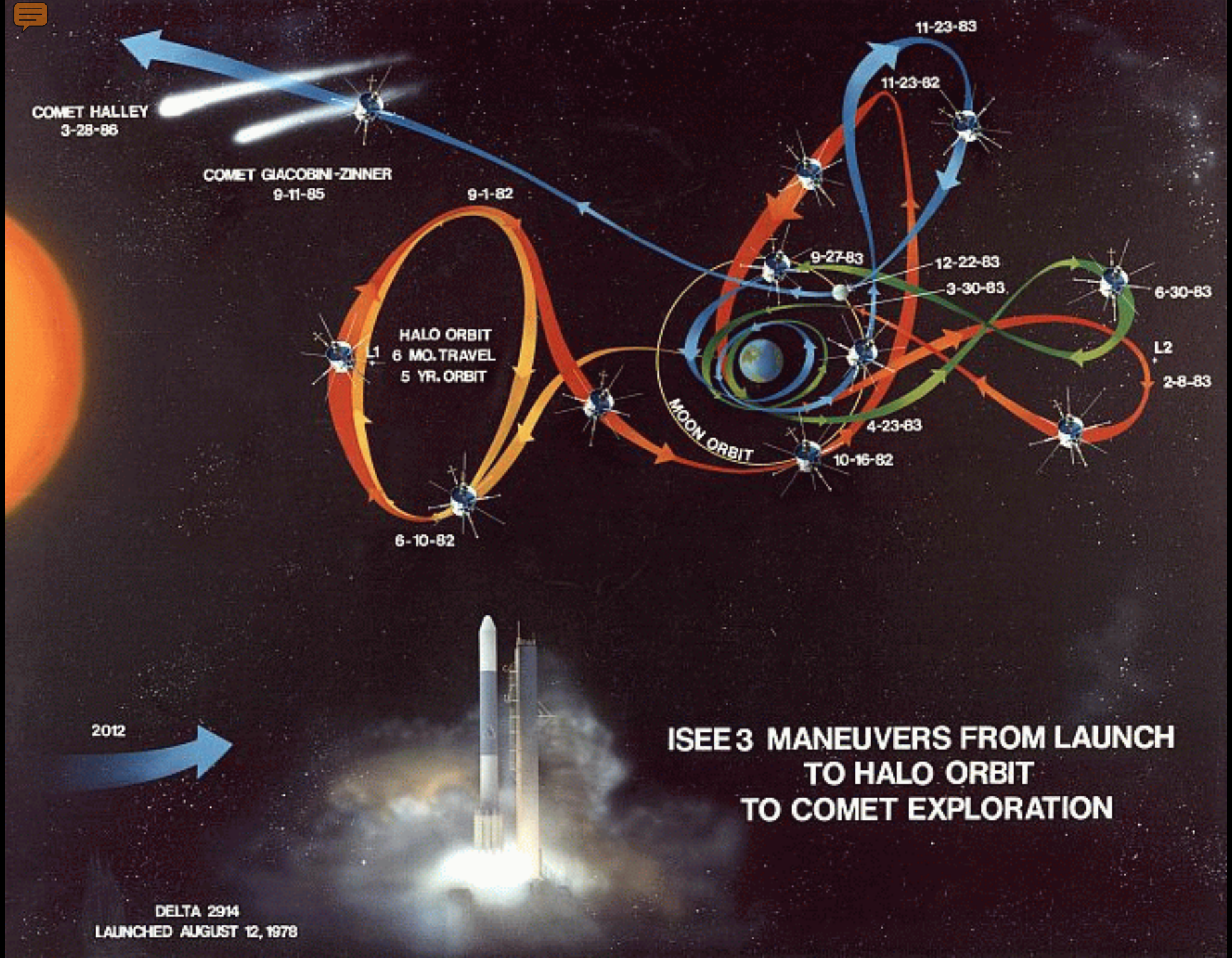
ISEE-3

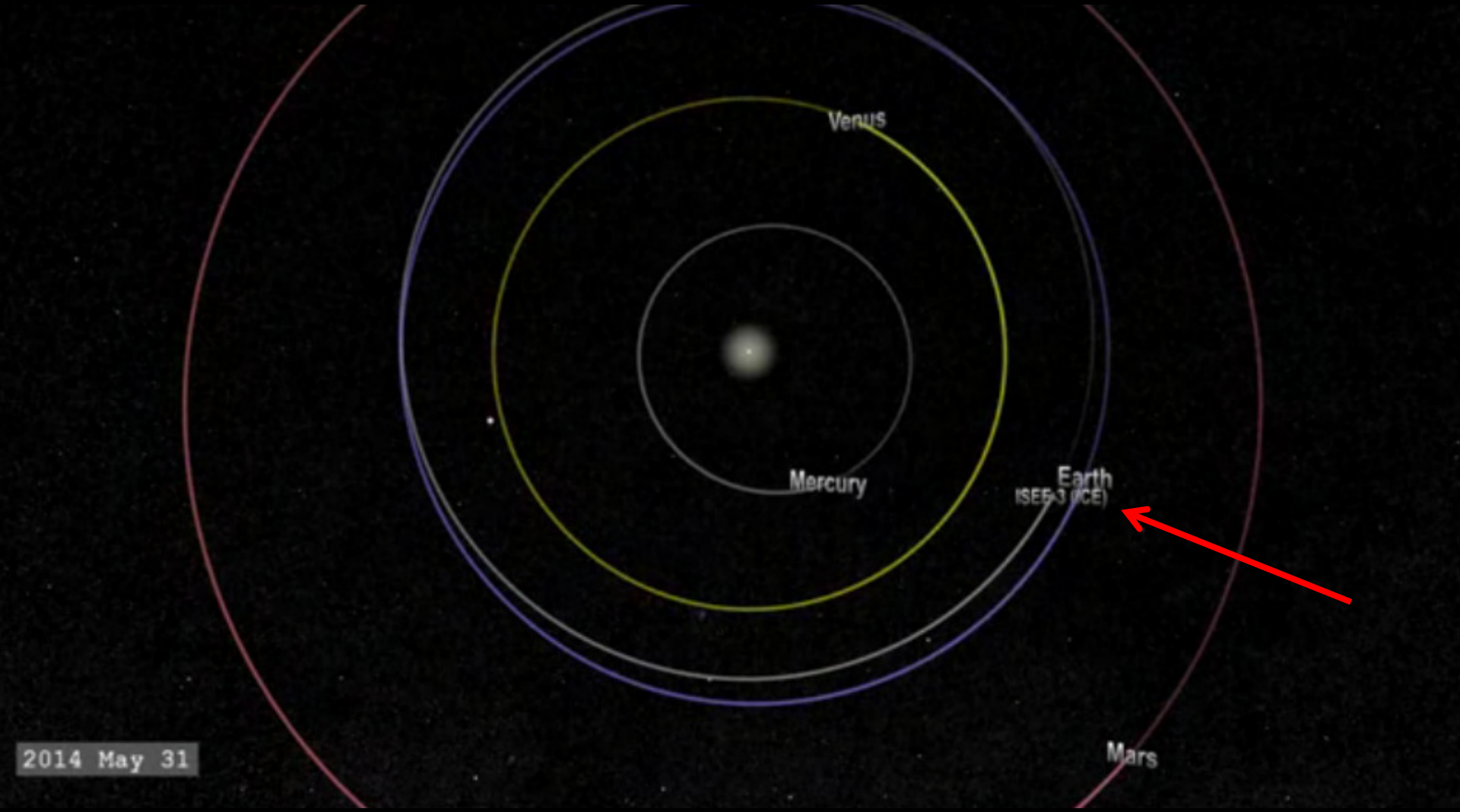
- **I**nternational **S**un/**E**arth **E**xplorer 3
- Launched: August 12, 1978
- Heliocentric Orbit
- Study interaction between solar wind and Earth's magnetic field

ISEE-3

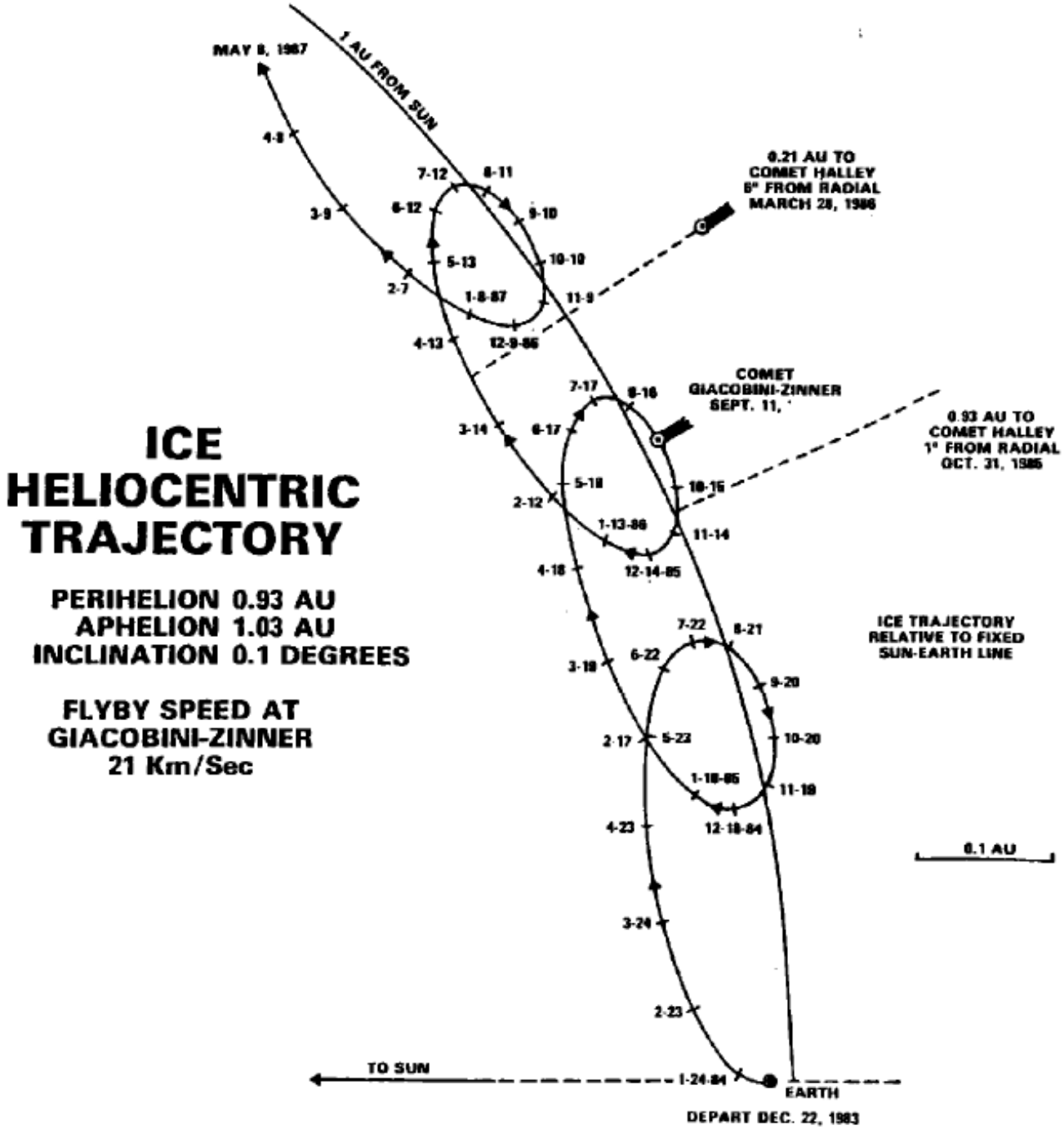
- Renamed ICE: **I**nternational **C**ometary **E**xplorer
- First spacecraft in halo orbit at an Earth-Sun L1 (Lagrange point)
- First spacecraft to pass through tail of a comet (Giacobini-Zinner)

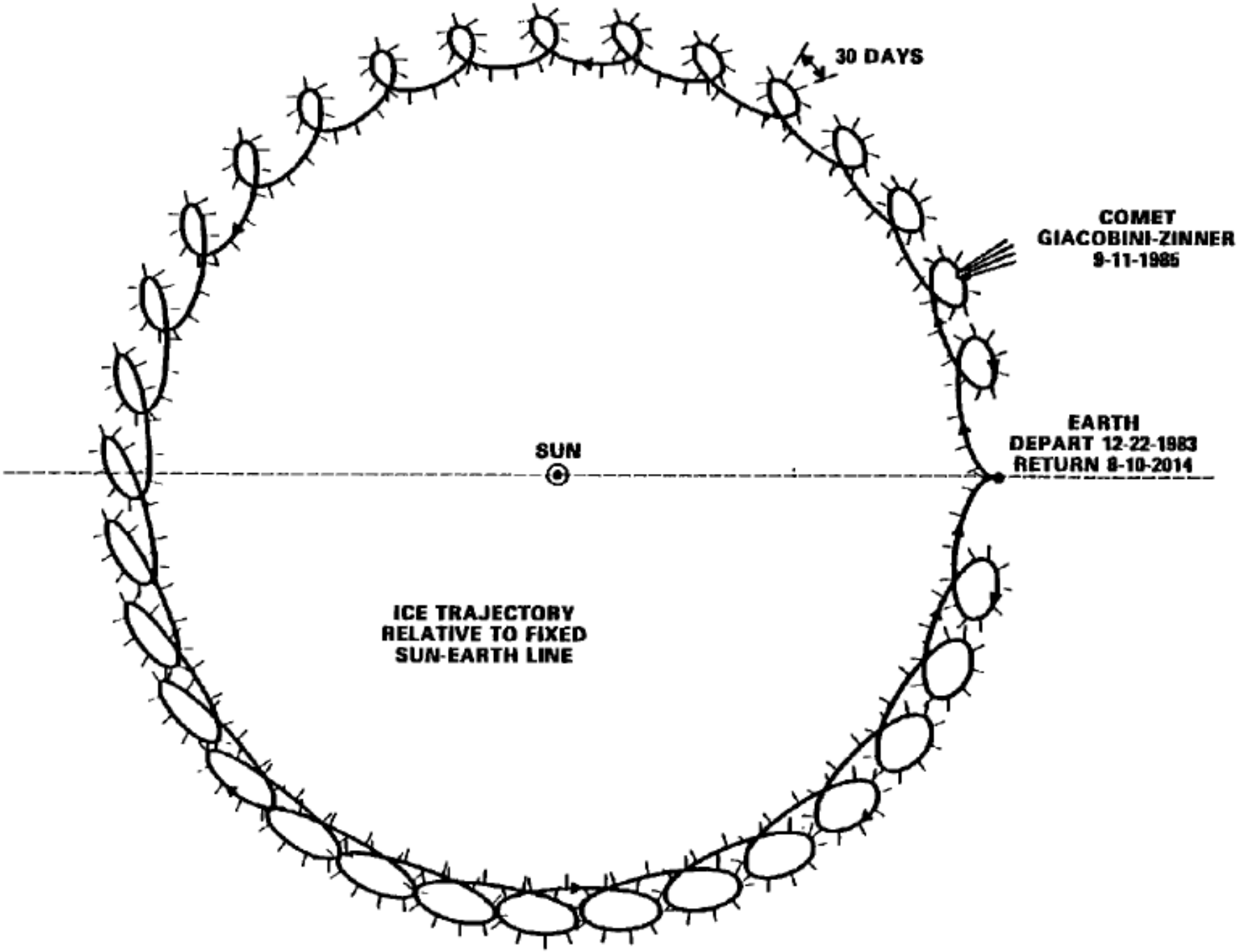

L4
L3
L1
L2
L5

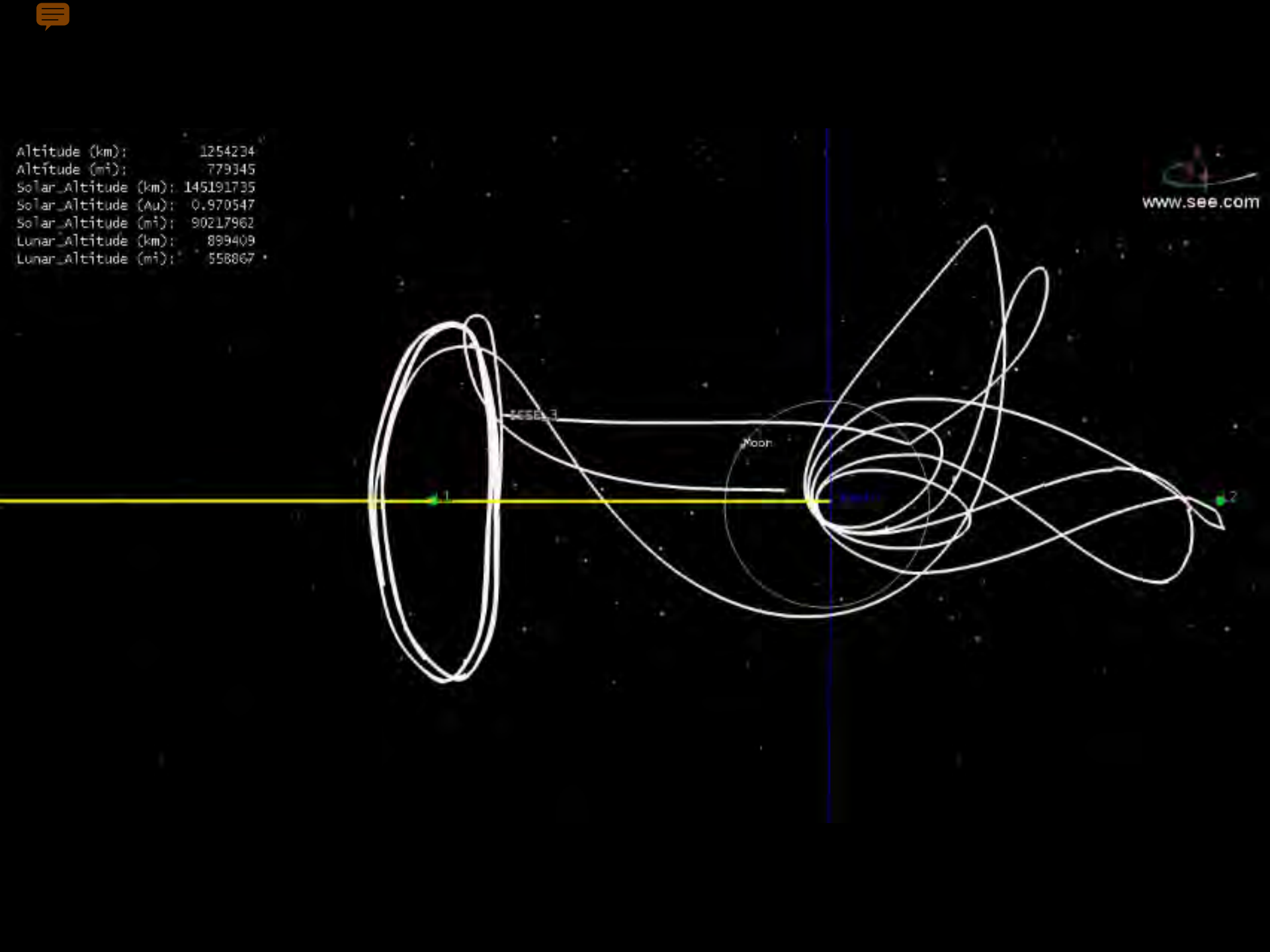

11-23-83
11-23-82
COMET HALLEY
3-28-86
COMET GIACOBINI-ZINNER
9-11-85
9-1-82
9-27-83
12-22-83
3-30-83
6-30-83
HALO ORBIT
6 MO. TRAVEL
5 YR. ORBIT
L1
L2
2-8-83
MOON ORBIT
4-23-83
10-16-82
6-10-82
2012
ISEE 3 MANEUVERS FROM LAUNCH
TO HALO ORBIT
TO COMET EXPLORATION
DELTA 2914
LAUNCHED AUGUST 12, 1978

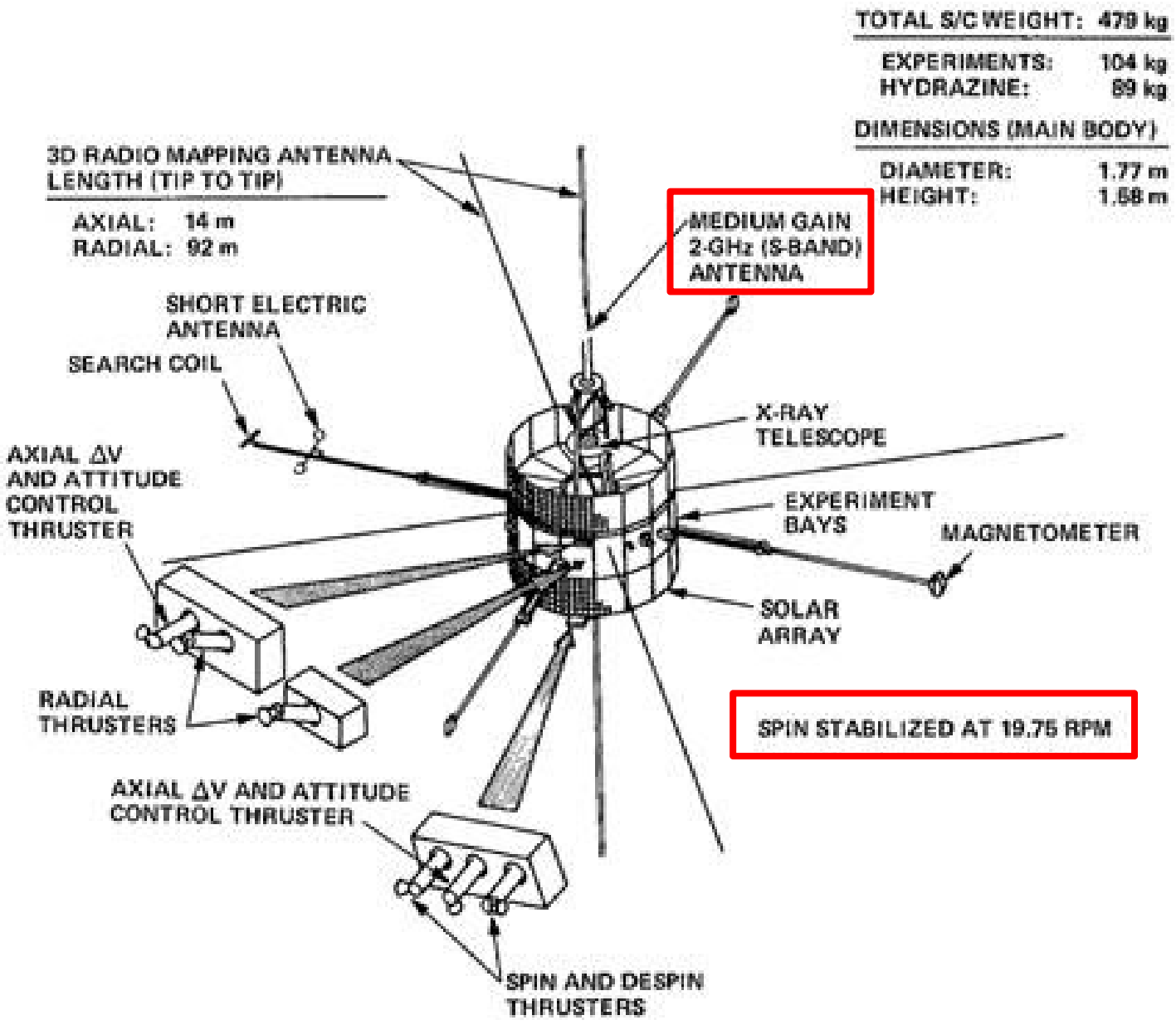


http://en.wikipedia.org/wiki/File:ISEE-3_%28ICE%29_Revisits_Earth.ogg


ICE
HELIOCENTRIC
TRAJECTORY
PERIHELION 0.93 AU
APHELION 1.03 AU
INCLINATION 0.1 DEGREES
FLYBY SPEED AT
GIACOBINI-ZINNER
21 Km/Sec
MAY 8, 1987
1 AU FROM SUN
4-8
3-9
2-7
4-13
5-13
6-12
7-12
8-11
9-10
10-10
11-9
1-8-87
12-9-86
0.21 AU TO
COMET HALLEY
8° FROM RADIAL
MARCH 28, 1986
COMET
GIACOBINI-ZINNER
SEPT. 11,
3-14
2-12
4-18
5-18
6-17
7-17
8-16
10-15
11-14
1-13-86
12-14-85
0.93 AU TO
COMET HALLEY
1° FROM RADIAL
OCT. 31, 1985
ICE TRAJECTORY
RELATIVE TO FIXED
SUN-EARTH LINE
3-19
2-17
4-23
3-24
2-23
6-22
7-22
8-21
9-20
10-20
11-19
5-22
1-18-85
12-18-84
0.1 AU
TO SUN
1-24-84
EARTH
DEPART DEC. 22, 1983


30 DAYS
COMET
GIACOBINI-ZINNER
9-11-1985
EARTH
DEPART 12-22-1983
RETURN 8-10-2014
SUN
ICE TRAJECTORY
RELATIVE TO FIXED
SUN-EARTH LINE


Altitude (km): 1254234
Altitude (mi): 779345
Solar_Altitude (km): 145191735
Solar_Altitude (Au): 0.970547
Solar_Altitude (mi): 90217962
Lunar_Altitude (km): 899409
Lunar_Altitude (mi): 558867
www.see.com
Moon
1
2

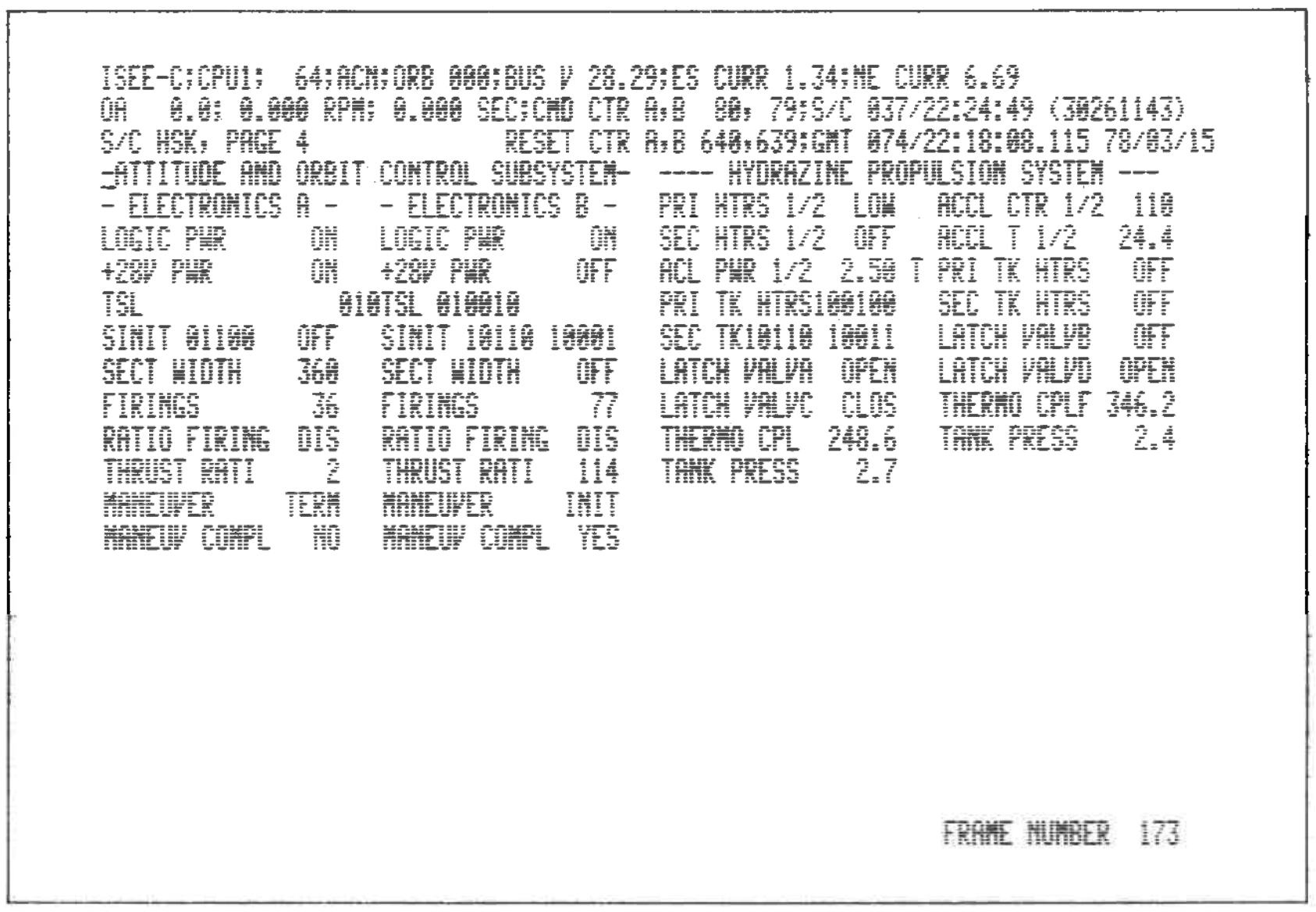

TOTAL S/C WEIGHT: 479 kg
EXPERIMENTS: 104 kg
HYDRAZINE: 89 kg
DIMENSIONS (MAIN BODY)
DIAMETER: 1.77 m
HEIGHT: 1.58 m
3D RADIO MAPPING ANTENNA LENGTH (TIP TO TIP)
AXIAL: 14 m
RADIAL: 92 m
MEDIUM GAIN 2-GHz (S-BAND) ANTENNA
SHORT ELECTRIC ANTENNA
SEARCH COIL
X-RAY TELESCOPE
AXIAL ΔV AND ATTITUDE CONTROL THRUSTER
EXPERIMENT BAYS
MAGNETOMETER
SOLAR ARRAY
RADIAL THRUSTERS
SPIN STABILIZED AT 19.75 RPM
AXIAL ΔV AND ATTITUDE CONTROL THRUSTER
SPIN AND DESPIN THRUSTERS

Science Instruments

Table 1. ICE investigations

Title	Principal Investigator	Affiliation	Experiment Status
Solar Wind Plasma*	Bame	Los Alamos National Lab	Electrons only (Ion Portion Failed)
Plasma Composition*	Ogilvie	GSFC	Operational
Magnetometer*	Smith	JPL	Operational
Plasma Waves*	Scarf	TRW Systems	Operational
Energetic Protons*	Hynds	Imperial College, London	Operational
Radio Waves*	Steinberg	Paris Observatory, Meudon	Operational
X-Rays, Low Energy Electrons	Anderson	UCB	X-Rays and E > 200 keV (Low Energy Electron Portion Failed)
Low Energy Cosmic Rays	Hovestadt	MPI	Partial Failure (Ulezeq)
Medium Energy Cosmic Rays	von Rosenvinge	GSFC	Operational
High Energy Cosmic Rays	Stone	CIT	Partial Failure (Isotope Portion)
High Energy Cosmic Rays	Heckman	UCB/LBL	Partial Failure (Drift Chamber)
Cosmic Ray Electrons	Meyer	University of Chicago	Operational
Gamma Ray Bursts	Teegarden	GSFC	Partial Failure (PHA Memory)

Old Telemetry Screen



```
ISEE-C;CPU1;  64;ACN;ORB 000;BUS V 28.29;ES CURR 1.34;ME CURR 6.69
OA   0.0; 0.000 RPM; 0.000 SEC;CMD CTR A,B  00, 79;S/C 037/22:24:49 (38261143)
S/C HSK, PAGE 4                RESET CTR A,B 640,639;GMT 074/22:18:00.115 78/03/15
-ATTITUDE AND ORBIT CONTROL SUBSYSTEM-  ---- HYDRAZINE PROPULSION SYSTEM ---
- ELECTRONICS A -    - ELECTRONICS B -  PRI HTRS 1/2  LOW   ACCL CTR 1/2  110
LOGIC PWR      ON   LOGIC PWR      ON   SEC HTRS 1/2  OFF   ACCL T 1/2   24.4
+28V PWR       ON   +28V PWR      OFF   ACL PWR 1/2  2.50 T PRI TK HTRS   OFF
TSL              0101TSL 010010         PRI TK HTRS100100   SEC TK HTRS   OFF
SINIT 011000   OFF   SINIT 10110 10001  SEC TK101110 10011   LATCH VALVB   OFF
SECT WIDTH     360   SECT WIDTH     OFF  LATCH VALVA  OPEN   LATCH VALVD  OPEN
FIRINGS         36   FIRINGS         77  LATCH VALVC  CLOS   THERMO CPLF 346.2
RATIO FIRING   DIS   RATIO FIRING   DIS  THERMO CPL   248.6   TANK PRESS    2.4
THRUST RATI      2   THRUST RATI    114  TANK PRESS     2.7
MANEUVER      TERM   MANEUVER      INIT
MANEUV COMPL    NO   MANEUV COMPL  YES

                                                    FRAME NUMBER  173
```

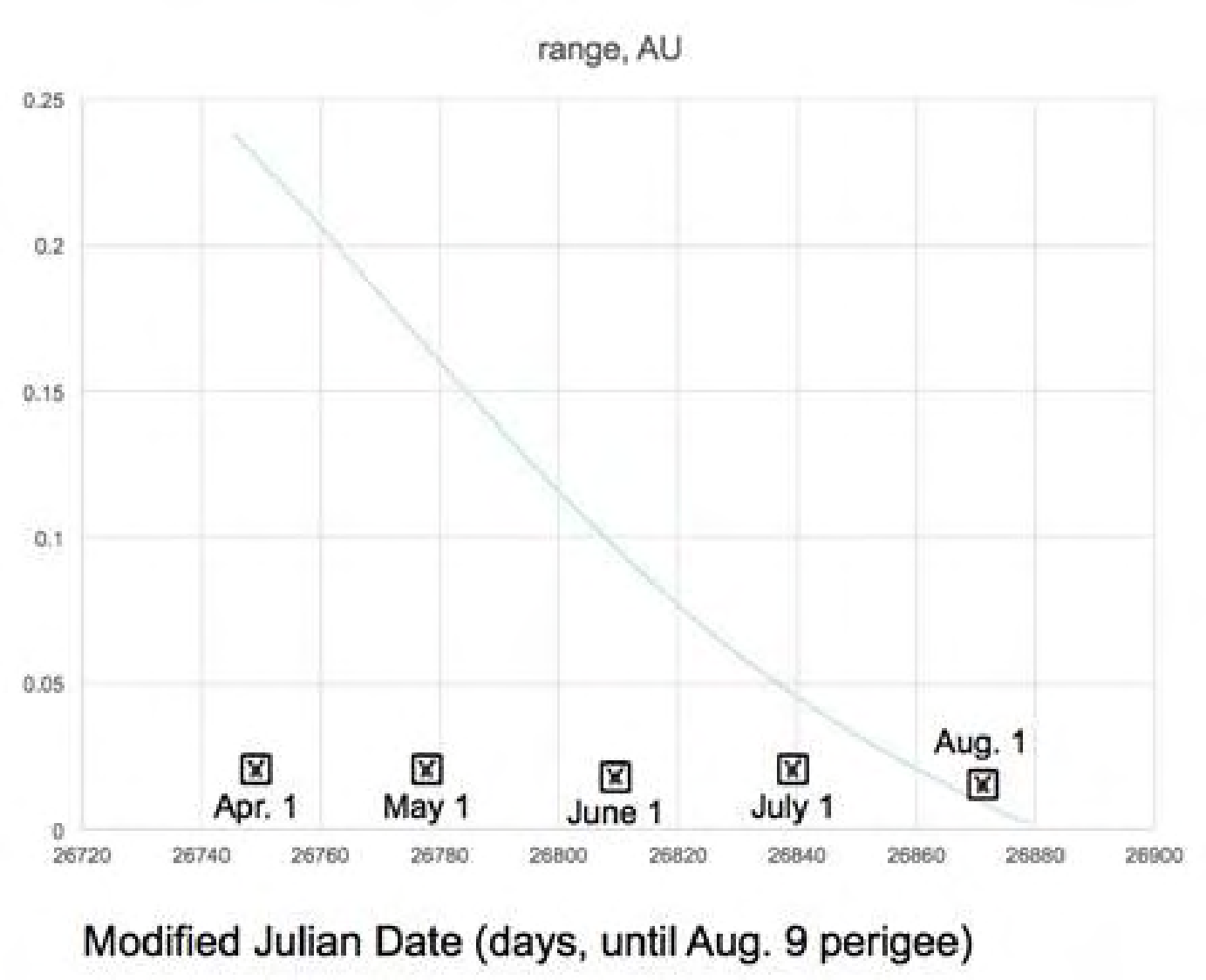
Loss of Interest

- Original mission drew to a close
- Telemetry disabled
  - Only transponders' carriers remain enabled
- NASA decommissioned ground-based equipment originally used to communicate with spacecraft
  - **D**eep **S**pace **N**etwork now incapable of sending commands
- Documentation has been scattered

(New) Mission

- Led by Dennis Wingo (Skycorp Inc) & Keith Cowing (Space College/NASA Watch/ SpaceRef)
- Re-capture ISEE-3 (command the spacecraft)
  - Enable telemetry (and decode)
  - Fire thrusters
- Bring into stable high-Earth orbit
- Allow open, public access to remaining operational scientific capabilities
- “NASA Signs Agreement with Citizen Scientists Attempting to Communicate with Old Spacecraft”

Closing In

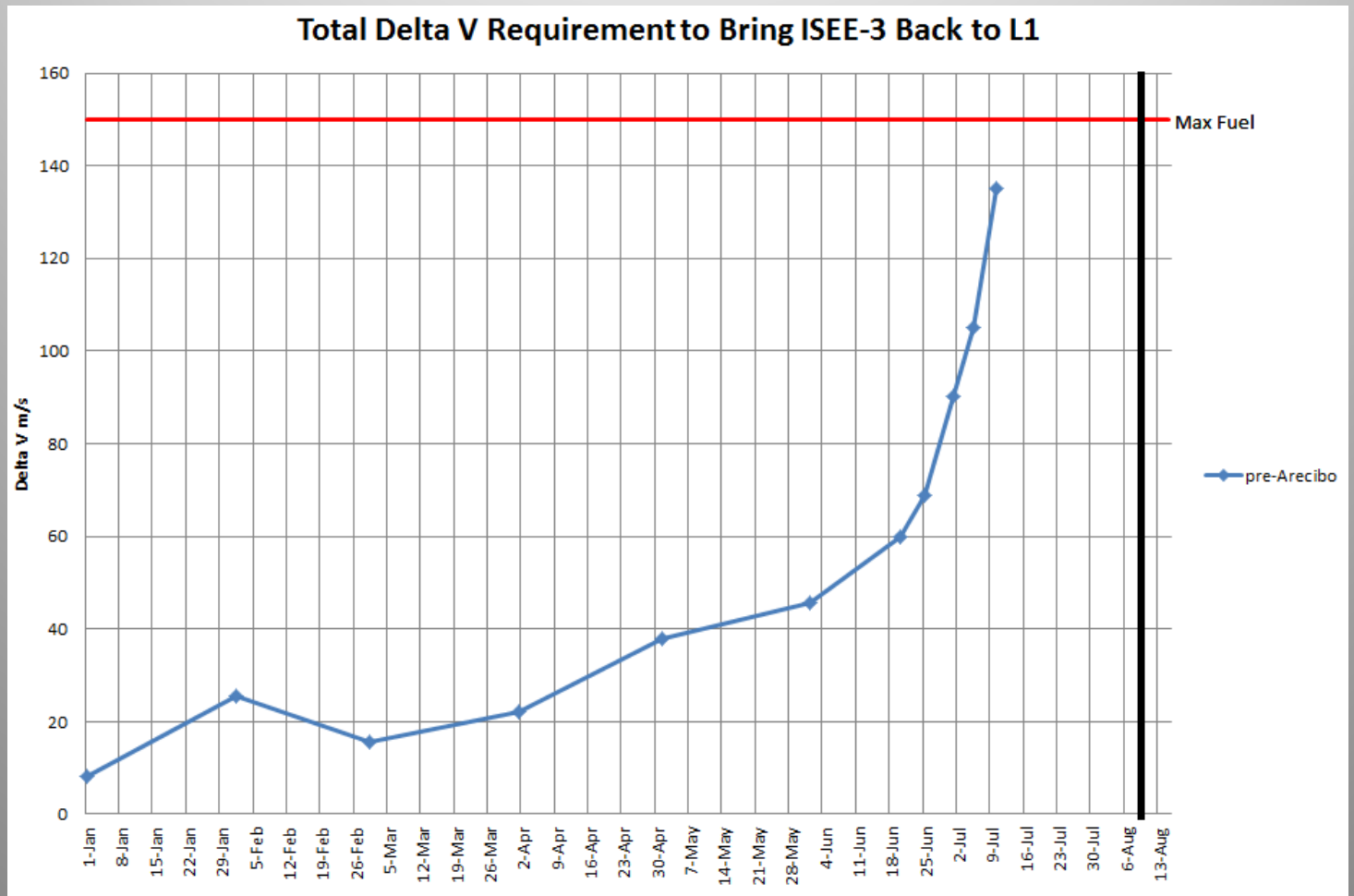

range, AU
0.25
0.2
0.15
0.1
0.05
0
26720
26740
26760
26780
26800
26820
26840
26860
26880
26900
Apr. 1
May 1
June 1
July 1
Aug. 1
Modified Julian Date (days, until Aug. 9 perigee)

A Sense of Urgency

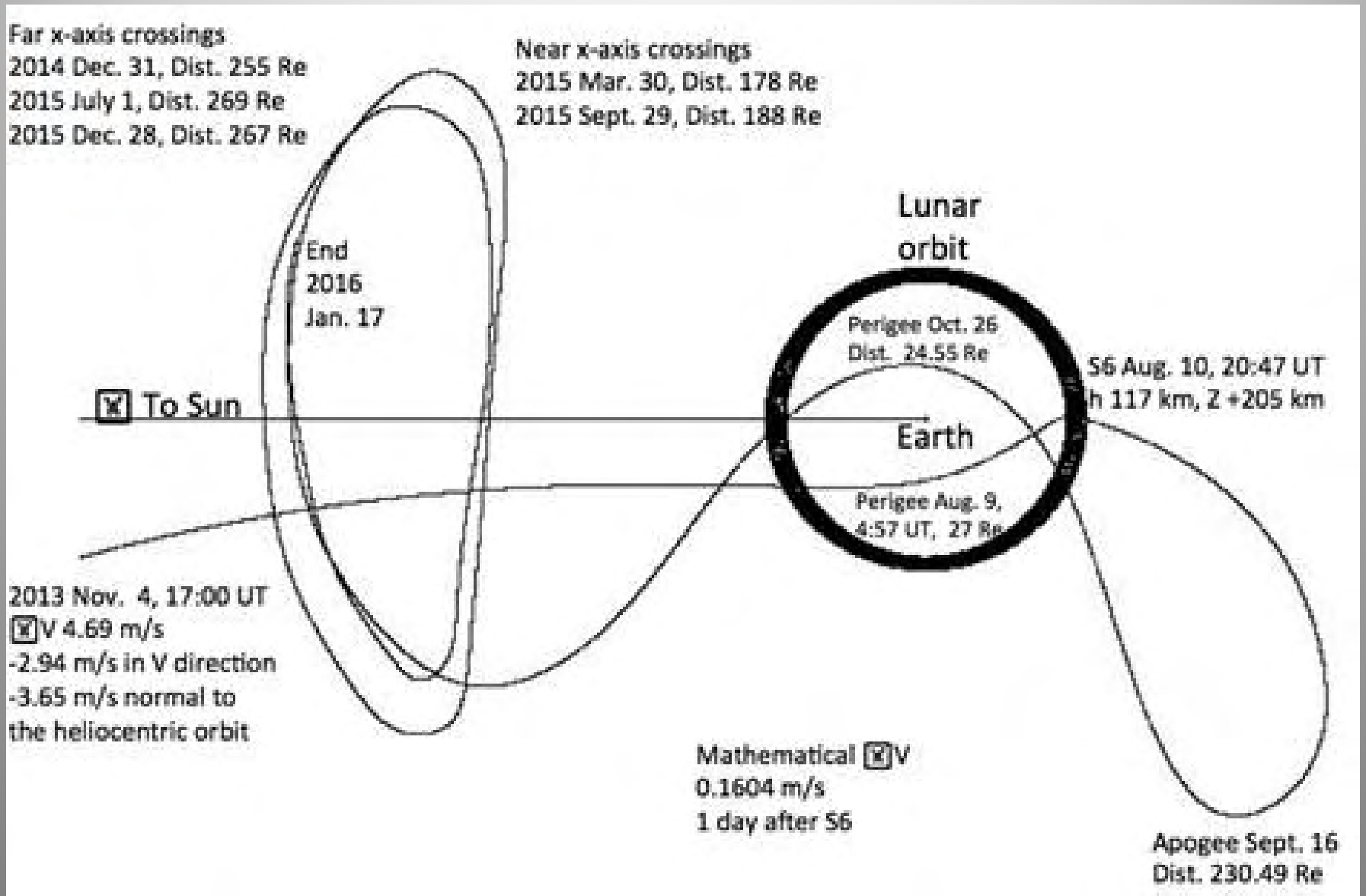
Date	Total ΔV, m/s	% ΔV capacity	Earth Dist., km	Dist. AU
2013 Aug 1	6.351	4.23	28167878	0.1883
2013 Sep 1	4.720	3.15	28515162	0.1906
2013 Oct 1	4.130	2.75	32859724	0.2197
2013 Nov 1	6.280	4.19	39182694	0.2619
2013 Dec 1	7.352	4.90	44871161	0.2999
2014 Jan 1	8.355	5.57	48294364	0.3228
2014 Feb 1	25.645	17.10	47706709	0.3189
2014 Mar 1	15.691	10.46	43242137	0.2891
2014 Apr. 1	22.260	14.84	34636672	0.2315
2014 May 1	38.029	25.35	24450043	0.1634
2014 Jun 1	45.718	30.48	14415499	0.0964
2014 Jul 1	90.318	60.21	6875760	0.0460
2014 Aug 1	360.000	240.00	1435851	0.0096

A Sense of Urgency

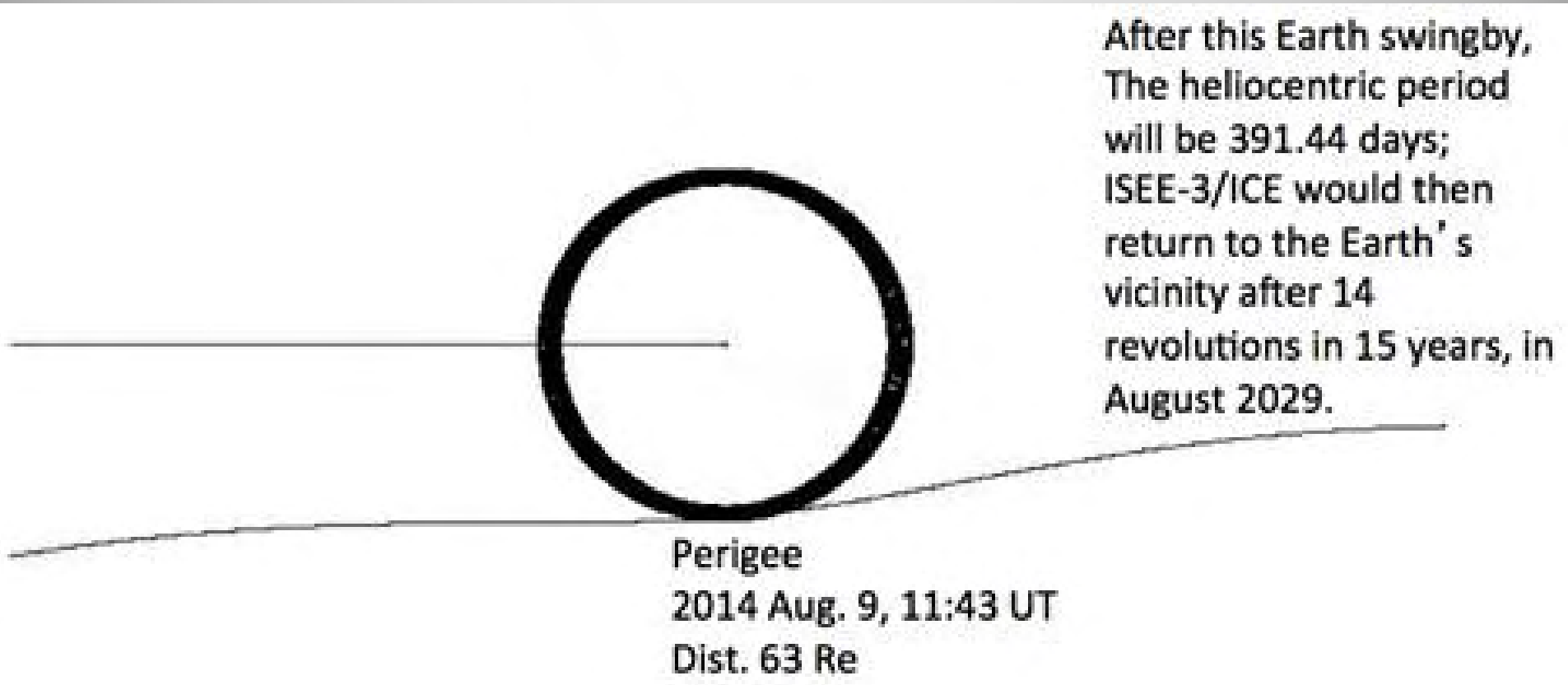
- Limited fuel remains for ΔV manoeuvres



Success Case



Failure Case



Crowdfunding

ROCKETHUB
The world's crowdfunding machine.

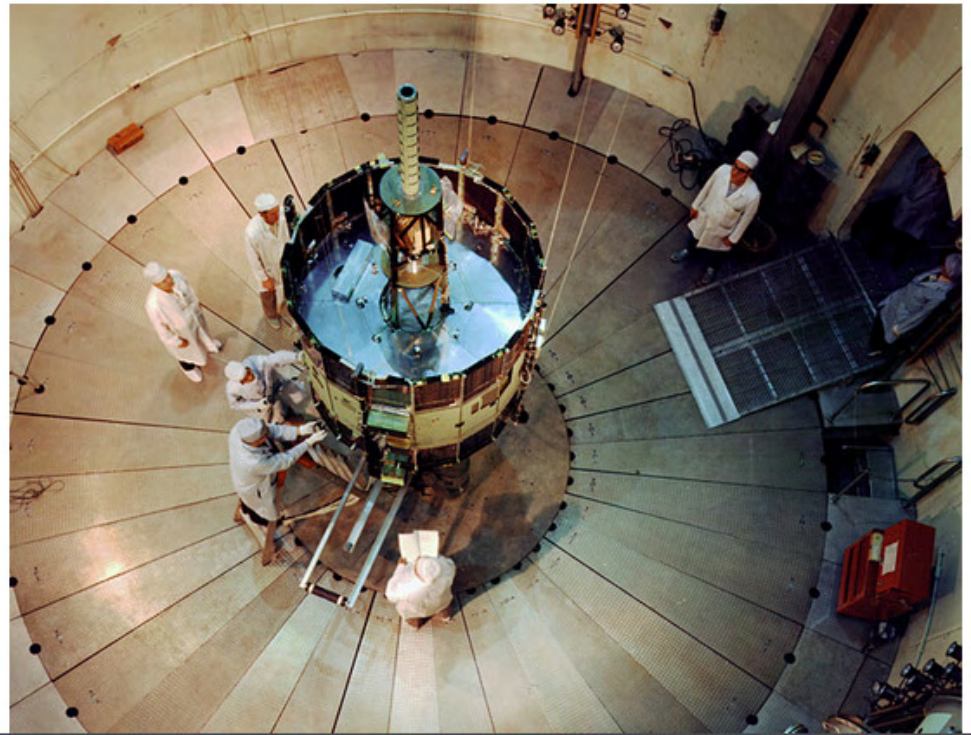
SUCCESS SCHOOL | OUR MOVEMENT | LATEST NEWS

Join | Login

Search Projects... Go

ISEE-3 Reboot Project by Space College, Skycorp, and SpaceRef

Description | About | Conversations | Activity



Project Leaders


Dennis Wingo


Keith Cowing

128%

$159,602
Raised towards
$125,000 goal

2238 **Funders**

Ended 05/23/14

Complete!

PROJECT COMPLETE

Funders




View All

Communications

- Radio communications required to contact & command the space craft
- Original equipment not available
- Need to quickly create a new modulator & demodulator
- Enter Software Defined Radio…

Create a new MODEM

Ettus Research Helps Power ISEE-3 Reboot Effort

By Keith Cowing on May 8, 2014 5:03 PM

USRP N210 units delivered to ISEE-3 Mission Control today. *"The USRP N210 provides high-bandwidth, high-dynamic range processing capability. The USRP N210 is intended for demanding communications applications requiring this type of rapid development"* Larger image.

Skycorp Incorporated and Ettus Research, a subsidiary of National Instruments, have joined forces for the development of a crucial piece of hardware needed to contact the ISEE-3 spacecraft. Contacting ISEE-3, launched by NASA in 1978, is the focus of the ISEE-3 Reboot Project. ISEE-3 will be returning to Earth orbit in August of this year after having circled the sun for nearly four decades. SpaceRef Interactive, Skycorp, and Space College have joined forces to rescue the spacecraft, put it back into orbit near Earth, and use it for scientific research and STEM education.

Long-distance Communications

- ~15.5 million km
- Spacecraft has a 5W transmitter
  - Two transponders (up- & down-link)
  - Two antennas (medium & intermediate gain)
- Not-your-average link budget

Python Real-time Tracker

- Uses predictions from JPL HORIZONS service
- Originally based on ephemeris updated in 2008
  - Derived from trajectory analysis by KinetX Aerospace
- Spacecraft has deviated from predicted path
  - Required manual sky search to find peak carrier signal
- Now updated from Arecibo ‘spider search’

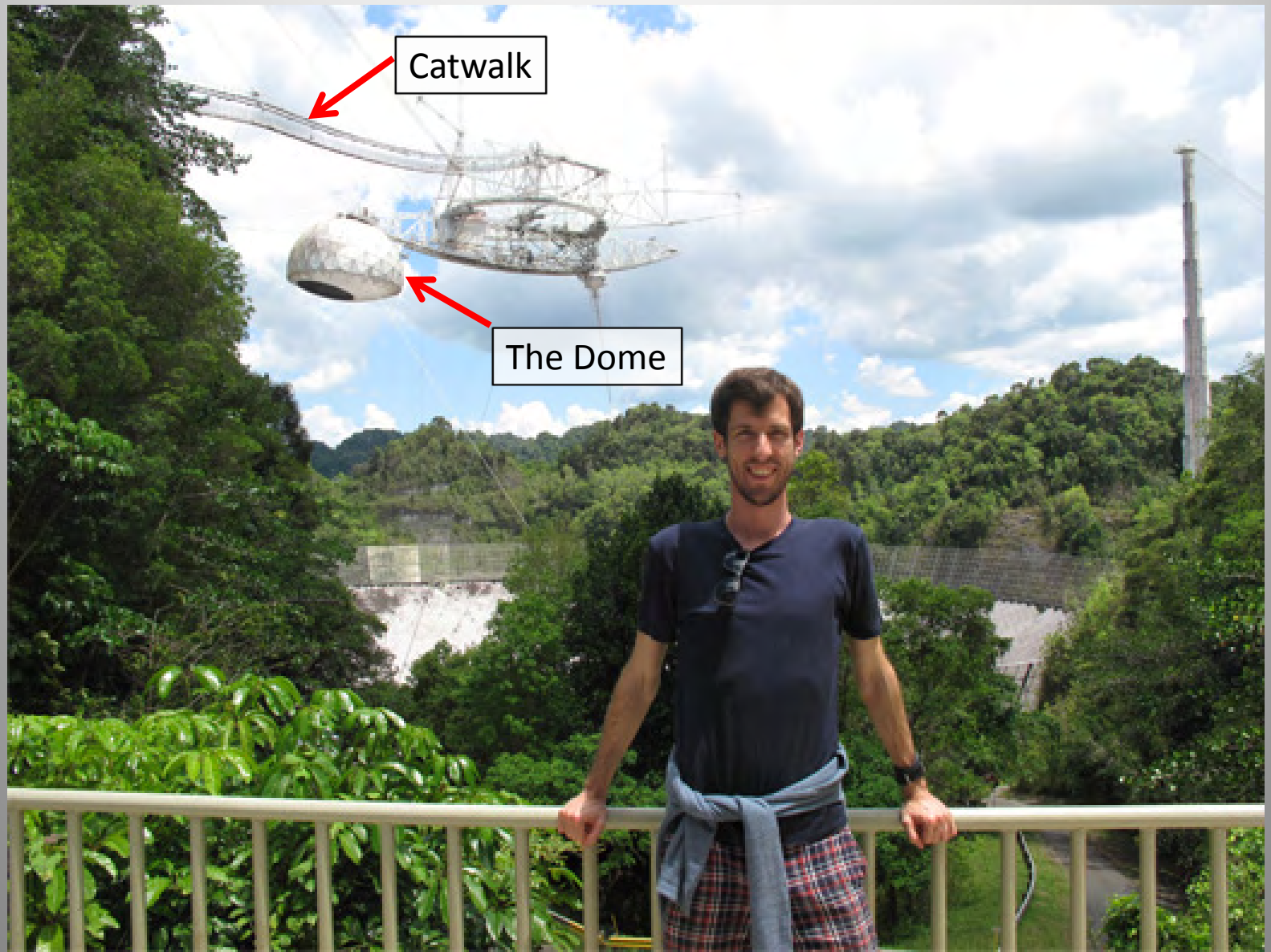
Python Real-time Tracker

```
UTC   : 2014-05-28 07:50:06.234132
Local: 2014-05-28 03:50:06.234096 (-4.0)

Lines: 471/2881 (2410 left)

Speed (km/s) : -3.4829406
Speed (m/s)  : -3482.9406368
Speed (km/hr): -12538.5862925

Dist (AU) : 0.10369466811595
Dist (km) : 15512501.553089

Light time (one-way) : 51.744135 s
Light time (two-way) : 103.488271 s

R.A.:  7.7720059526
Decl: +21.4076608943
(adjusted for light time)

Downlink frequencies:

2.270400000 GHz: 2.270426377 GHz (+26.377449 kHz)
2.217500000 GHz: 2.217525763 GHz (+25.762858 kHz)
```

Long-distance Communications

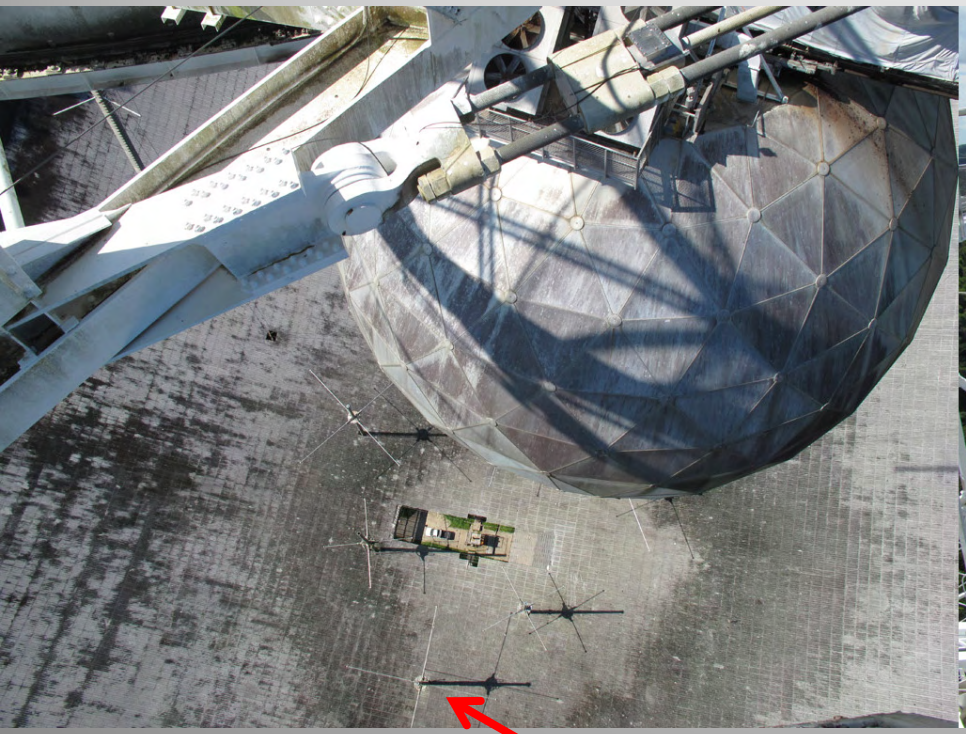
- Need:
  - a big amplifier
  - a big dish

Arecibo Radio Observatory



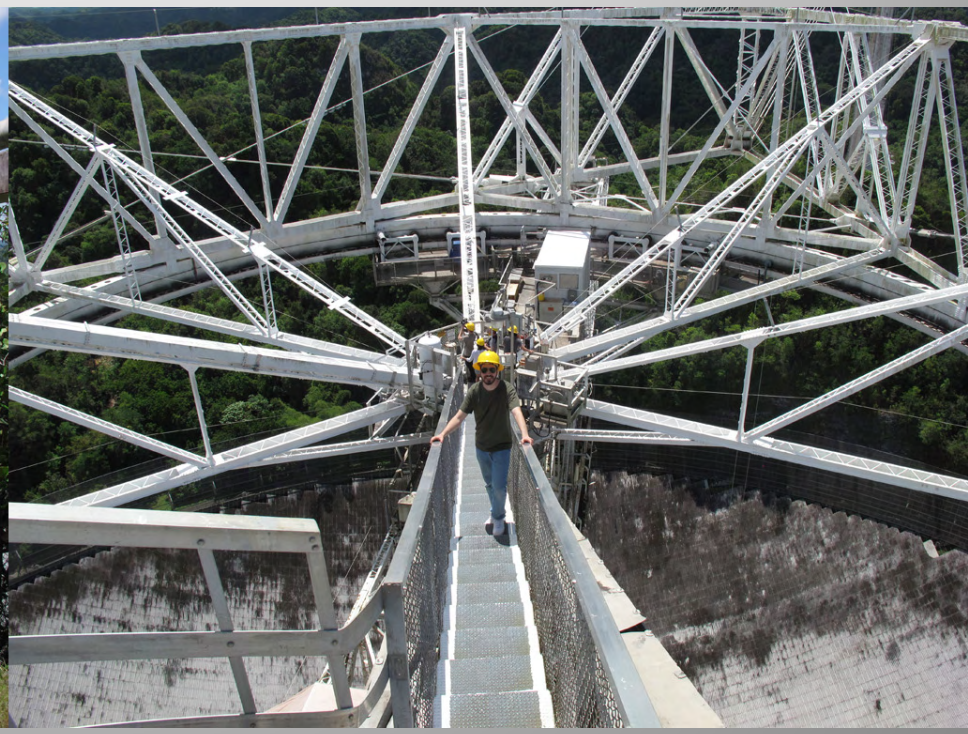
Arecibo Radio Observatory

View from above



Ionospheric heaters

View from above



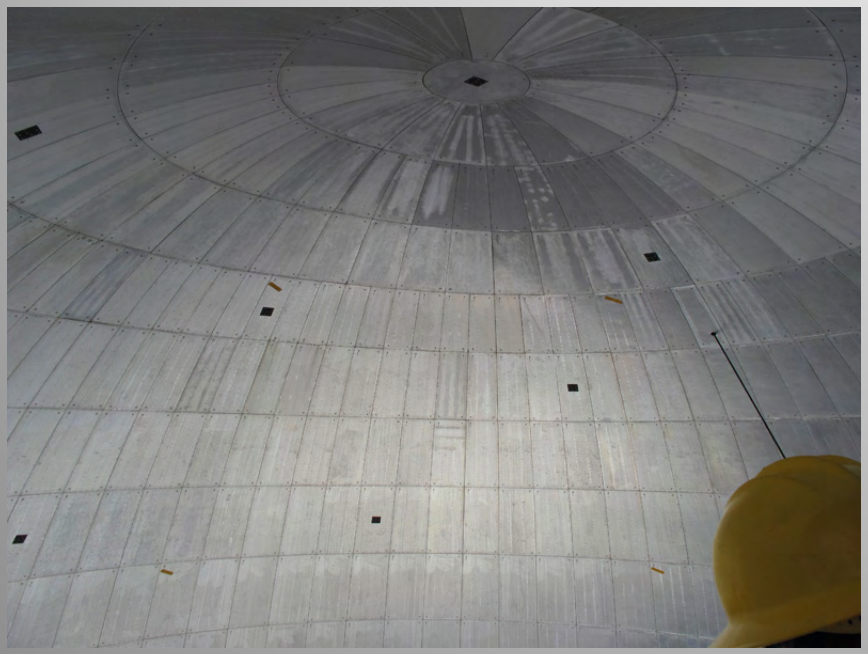
On the Structure

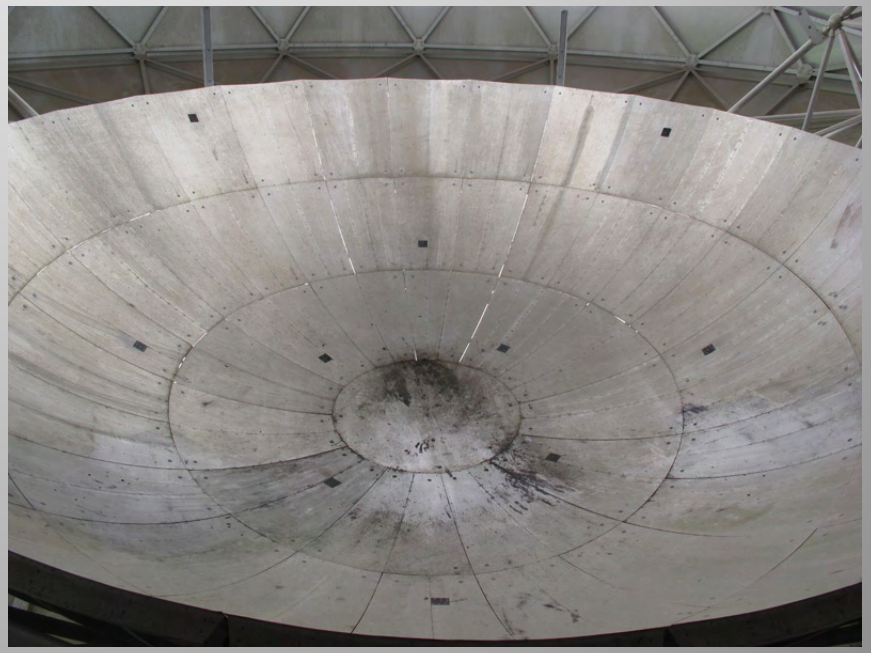
Under the Azimuth Arm

Cable Car & Underneath the Dome

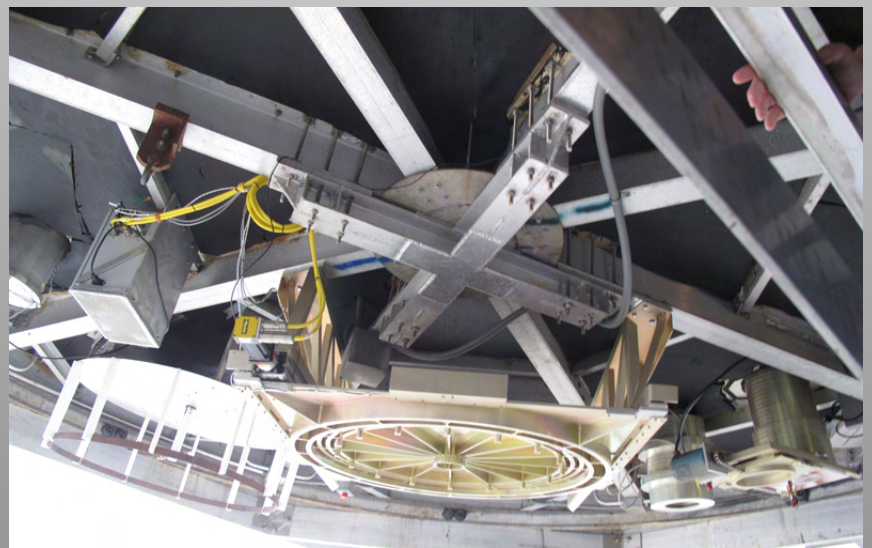
Dome Reflectors

- Secondary & tertiary bring photons to focus



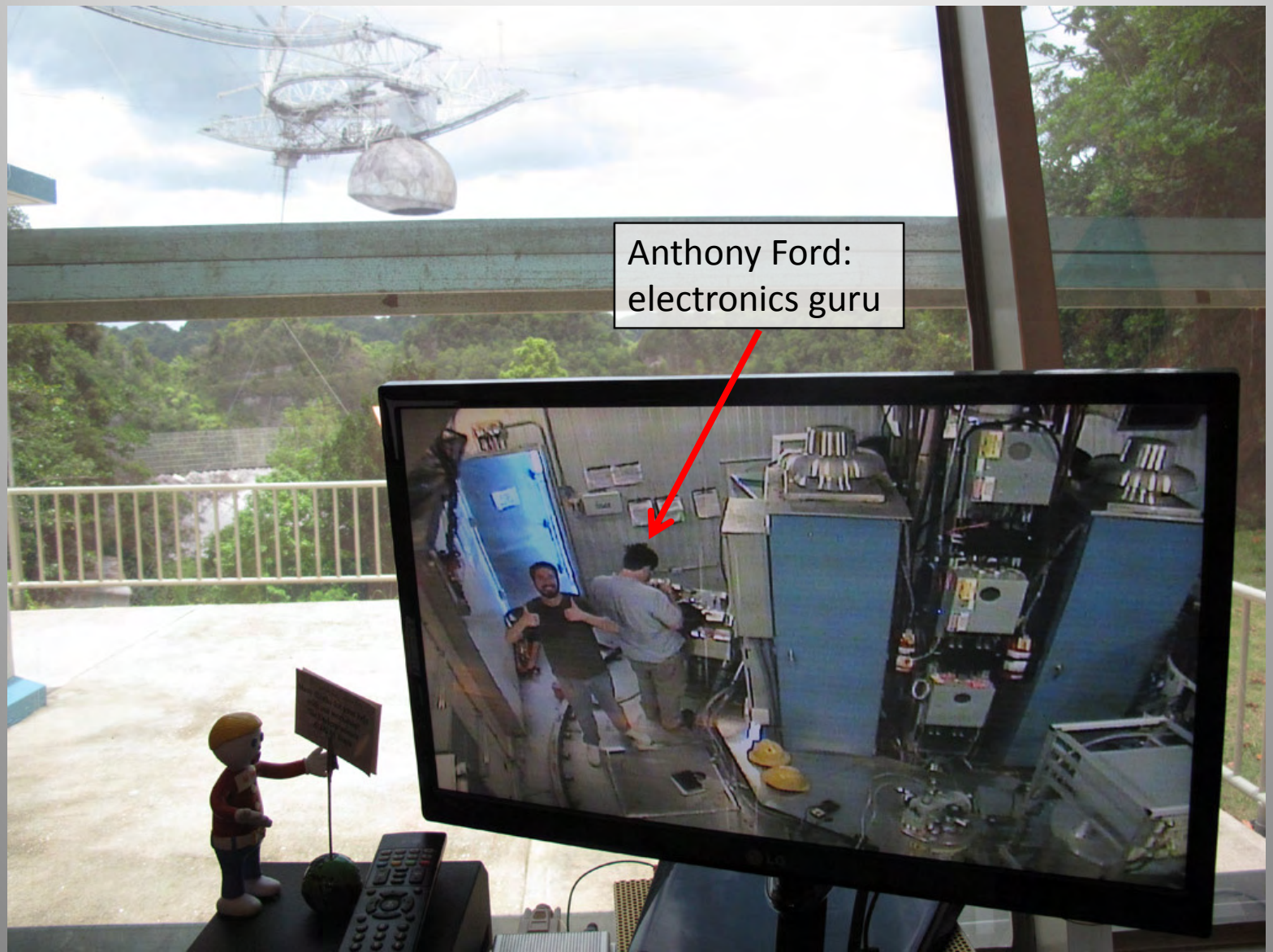


Feeds with Protective Shutters



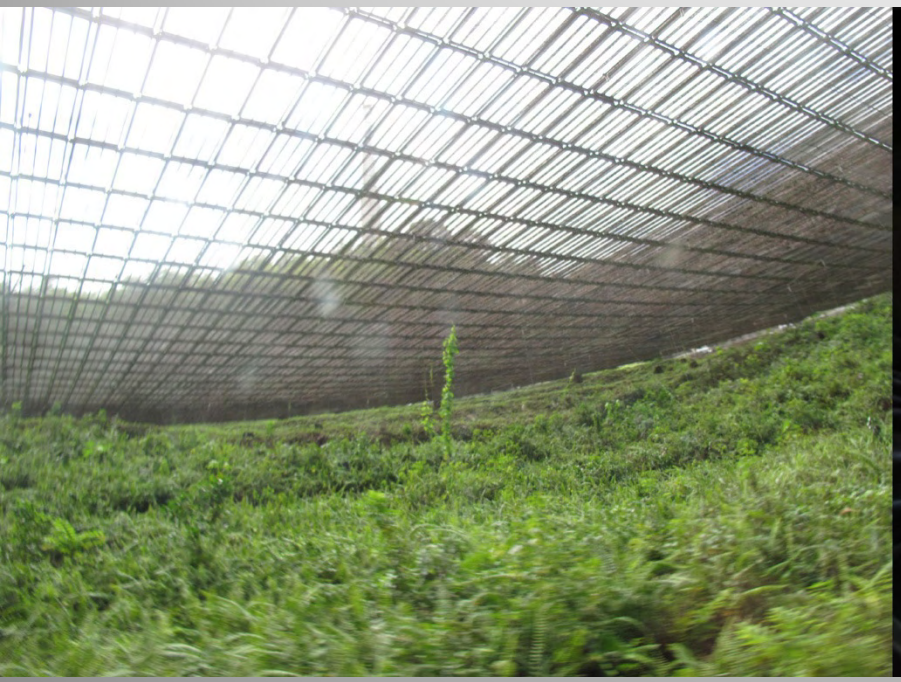
Telescope Operator's Station

CCTV on the Receiver Floor



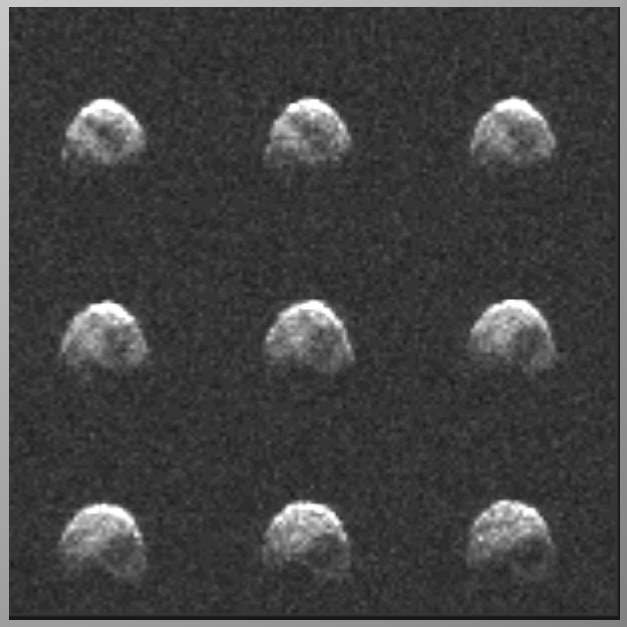
RFI is a real issue here

Under the Dish



Arecibo Radio ~~Observatory~~ Transmitter

- Already setup for S-band RADAR
  - Planetary RADAR astronomy (e.g. asteroids)
- Dish gain of ~73-75 dB



Arecibo Radio ~~Observatory~~ Transmitter

- Already setup for S-band RADAR
  - Planetary RADAR astronomy (e.g. asteroids)
- Dish gain of ~73-75 dB
- Narrow beamwidth (limited steering)
  - Need for accurate ephemeris
  - Signal considerably attenuated in beam sidelobes both for TX & RX (when pointing is not directly on target)

Arecibo Radio Transceiver

- Use existing S-band wideband (SBW) receiver
  - Tsys ~35-40 K
- Uplink frequency is outside range of existing **dual 1 MW klystron** S-band transmitter
  - Need alternative for TX to contact space probe

Fun Facts

- S-band RADAR has ***<u>20 Terawatt EIRP</u>***
- Unlucky birds that fly through beam:
  - Are boiled
  - Fall onto dish
  - Catch fire
  - Reflect a lot of RF back into the dome (bad for receivers)

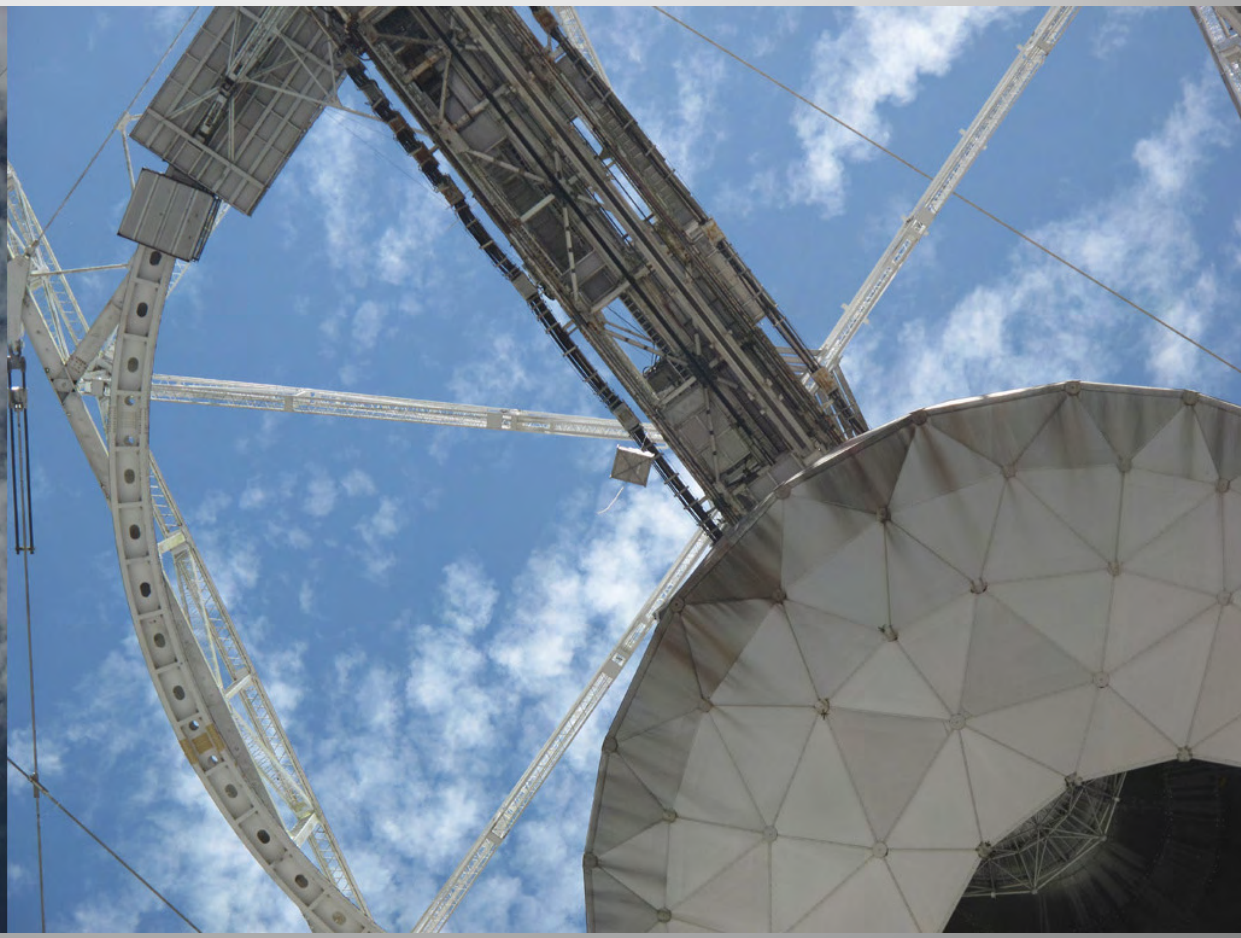
New S-band **P**ower **A**mplifier

- Built by Dirk Fischer (DK2FD) in Germany
  - Shipped overnight
- Consists of four UMTS-inspired amplifiers
  - Outputs combined to provide up to 450W
- Arecibo uses S-band waveguide to propagate signal
- Output of amplifier connected to waveguide transition & uses existing S-band feed

New S-band **P**ower **A**mplifier

Hoisting PA to the Dome

Hoisting PA to the Dome



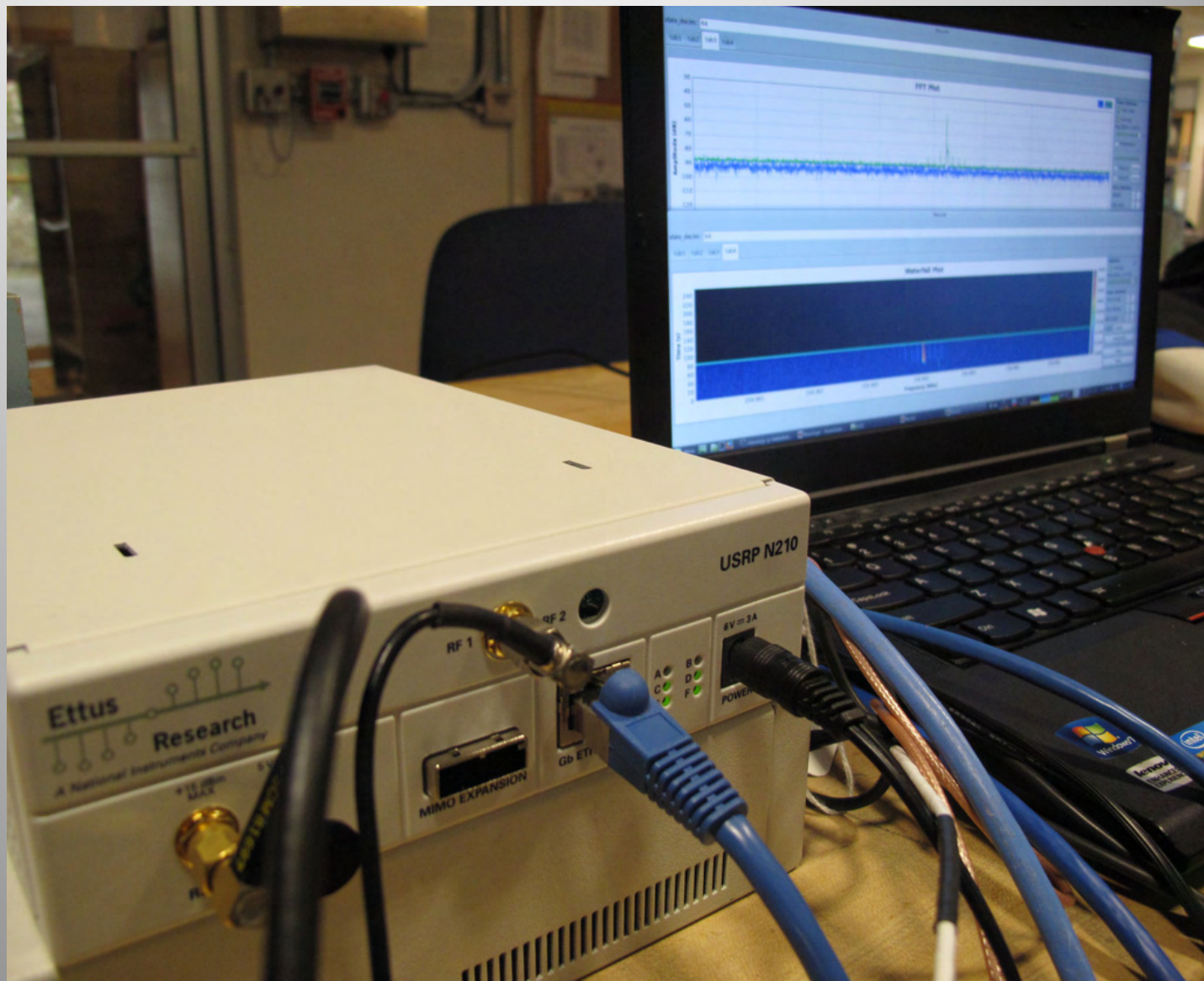
Hoisting PA to the Dome

Observation Time Window

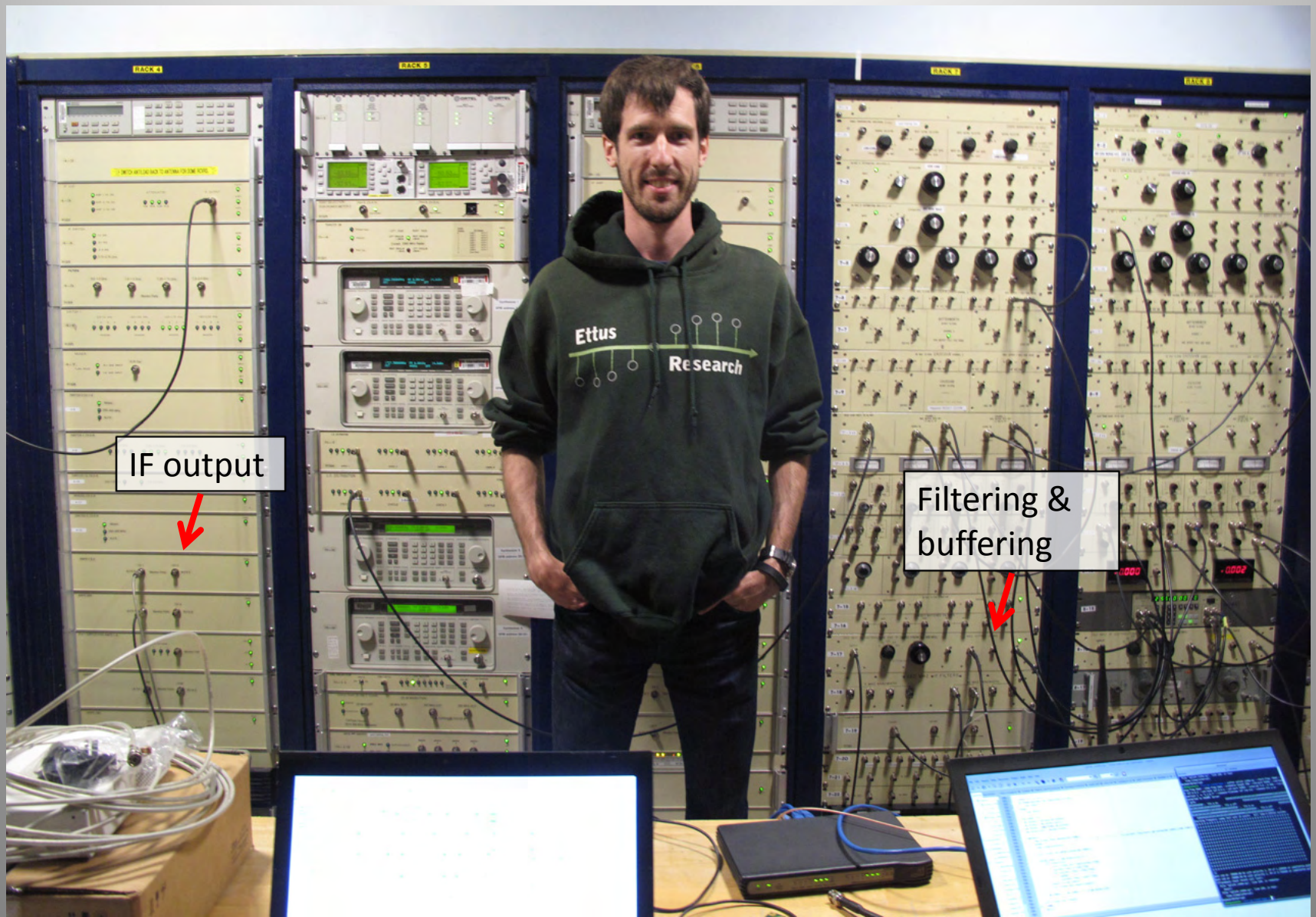
- Total ~2.75 hours each day in the afternoon
  - Space craft passes into arc that Arecibo can track
- Telescope schedule is incredibly busy
- We operate during ‘maintenance’ (unscheduled) periods
- Our actual window varies from day-to-day
- Switching between receiver and transmit takes time (floor rotation, receiver shutter extension)
- Switching between uplink frequencies takes time (PA calibration)

Receiver

- Two USRPs connected to IF output (260 MHz)
- Can choose between polarisation and downlink frequency



IF Panel



DOWNSTAIRS IF-LO SYSTEM
FUNCTIONAL BLOCK DIAGRAM

PAGE 1 OF 3: POL. A SIGNAL PATHS FIBER & HELIAX INPUTS, POWER METER 1 , ALFA MONITOR

file: ifdwn1.fc7
rev. APR. 7, 2005 JBH
rev 9 Feb 2009 DEW
last rev 01 Mar 2012 DEW

last rev 11 Apr 14 DEW

NOTES

1. "FP" = FRONT PANEL
2. "RP" = REAR PANEL
3. IF AMP IS CASCADE OF 1, 2, OR 3 10dB AMPS
4. 10.5 dB AMPS: COUGAR AC2546C, 16dBb OUT @ 1dB COMP.
5. 11dB AMPS: COUGAR AC559C, 20dBm OUT @ 1dB COMP.
6. 18dB AMPS: COUBAR AC2564C, 15.5 dBm OUT @ 1 dB COMP.
7. 23 dB AMPS: MCL ZX60-2522M, 18dBm OUT @ 1 dB COMP.
8. 16 dB AMPS: MCL ZX60-2514M, 16.5dBm OUT @ 1dB COMP.
9. 13 dB AMPS: MCL ZX60-2510M, 15.5dBm OUT @ 1dB COMP.
10. 21 dB AMPS: MCL ZFL-500HLN, 17dBm OUT @ 1dB COMP.

CIRCLES RESPRESENT PWR SPLITTERS. EXAMPLE

ALFA FIBER RECEIVER (SPECTROMETER ROOM)

FROM ALFA FRONT END

ALFA FIBERS POL A

DATA SELECTOR (1 OF 14)

ALFA MONITOR

To rack chassis 4-8 & 4-12

ALFA FIBERS POL B

To rack chassis 6-8 & 6-12

TRANSFER SWITCH RACK 5 (SEE SCHEM. SHEET 0)

2 TRANSFER (REVERSING) SWITCH:
EXAMPLE: if2 "if2_xfnormal T"
(USE F FOR REVERSED)

FIBER RECEIVER RACK 5

LHC FIBER FROM DOME

RHC AUX OUT

FROM UPSTAIRS IF/LO SYSTEM

LHC CARRIAGE HOUSE SIGNAL (CONVERTED TO 260 MHZ) FROM p. 3

5-4

10dB

RP TEST PORT

EXT CABLE

NOISE SOURCE 35 dB ENR

RP

REVERSING RELAY

POL B (TO PAGE 2)

RHC CARRIAGE HOUSE SIGNAL (CONVERTED TO 260 MHZ) FROM p. 3

RHC FIBER FROM DOME

Ortel 10450 01-6 GHz

LHC AUX OUT

FIBER RECEIVER RACK 5

1 SIGNAL SOURCE
EXAMPLE: if2 "if2_sigsrc grg"
(gr=greg, ch, noise)

RACK 5 LEFT HAND PWR METER

HP4412 PWR HEAD

DUAL CHANNEL POWER METER #1 HP E4419A

GPIB READ OUT

FROM POL B IF AMP (RACK 6)

HP4412 PWR HEAD

swap pol.

POL. A FILTERS RACK 4 (SEE SCHEM. SHEET 3)

BANDPASS 1.0 - 1.5 GHZ 1750

BANDPASS 1.25-1.75GHZ 1500

BANDPASS 1.5 - 2.0 GHZ 1250

4-5

IF SWITCH POL A RACK 4 (SEE SCHEM. SHEET 2)

4-4

1.0 - 2.0 GHZ "1500"

0.5-1 GHZ "750"

720-780 "750nb"

0.2-0.4 GHZ "300"

IF AMP POL A RACK 4 (SEE SCHEM. SHEET 1)

4-3

10,20,30dB

IF CH A TO PUPPI via "Coax 1"

CASCADE OF 1, 2, OR 3 10.5dB AMPS

3

4 INPUT DISTRIBUTOR:
if2 "if2_inpfrq 1500"
if2 "if2_inpfrq 750"
if2 "if2_inpfrq 750nb"
if2 "if2_inpfrq 300"
if2 "if2_inpfrq alfa"

NOM. 200 MHZ - 400 MHZ

NOM. 200 MHZ - 400 MHZ

GAIN:
EXAMPLE: if2 "if2_gain 14, 10"
(CHANNEL A: 14dB, CHANNEL B: 10dB)
RANGE: -11 TO 30

SWITCH 1 POL A CH 5-8 RACK 4 (SEE SCHEM. SHEET 6)

4-10

MIXERS POL A CH 5-8 RACK 4 (SEE SCHEM. SHEET 8)

4-11

SWITCH 2 POL A CH 5-8 RACK 4 (SEE SCHEM. SHEET 10)

4-12

500 MHZ LOW-PASS

LO 5A

LO 6A

LO 7B

LO 8A

ALFA 1A "ALFA 1"

ALFA 3A "ALFA 2"

ALFA 5A "ALFA 3"

ALFA "7A" "ALFA 4"

AMPS 5&6 POL A RACK 4 4-16

AMPS 7&8 POL A RACK 4 4-17

WAPP1 BOARD 2A

WAPP2 BOARD 2A

WAPP3 BOARD 2A

WAPP4 BOARD 2A

GALFA

8:1 SWITCH (FOR PWR METER 2)

5 MIXER SOURCE
8 INDEPENDENT SWITCHES
if2 "if2_mr m1 m2 m3 m4 m5 m6 m7 m8"
where m8 are all 750 or any mixture
of 175000, and 1250

SWITCH 1 POL A CH 1-4 RACK 4 (SEE SCHEM. SHEET 4)

4-6 (R1325)

2GHZ LOW PASS

MIXERS POL A CH 1-4 RACK 4 (SEE SCHEM. SHEET 7)

4-7 (R1326)

LO 1A

LO 2A

LO 3A

LO 4A

LO 1 CHB

VLB LO B

SWITCH 2 POL A CH 1-4 RACK4 (SEE SCHEM. SHEET 9)

4-8

ALFA "ALFA1" 0A

ALFA "ALFA2" 2A

ALFA "ALFA3" 4A

ALFA "ALFA4" 6A

AMPS 1&2 POL A RACK 4 4-13

AMPS 3&4 POL A RACK 4 4-14

PLANETARY DECODER

WAPP1 BOARD 1A

WAPP2 BOARD 1A

WAPP3 BOARD 1A

WAPP4 BOARD 1A

CORRELATOR

8:1 SWITCH (FOR PWR METER 2)

260 TO 30 CONVERTER

"coax 4" to backend room near puppi

JPL

HANKINS 1

HANKINS 2

VISITORS' ROOM

VLB 0.5-1GHz OUT

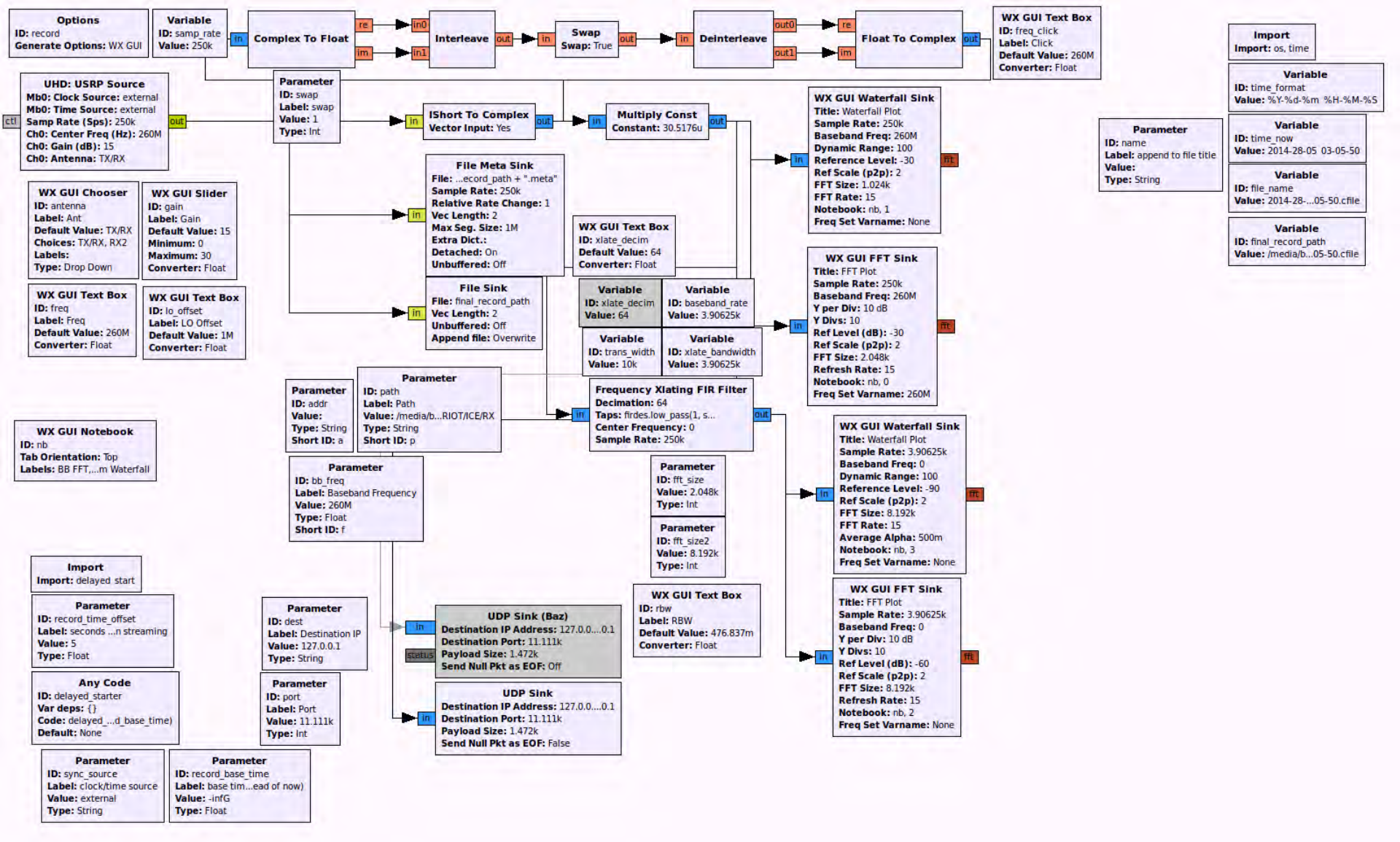
6 VLI GNAL SOURCE:
EIT if2 "if2_vlbainp 750"
OR "if2_vlbainp 1500"

CORRECT SWITCH 2 POSITIONS
ARE SELECTED BY if2_inpfrq

Synchronisation

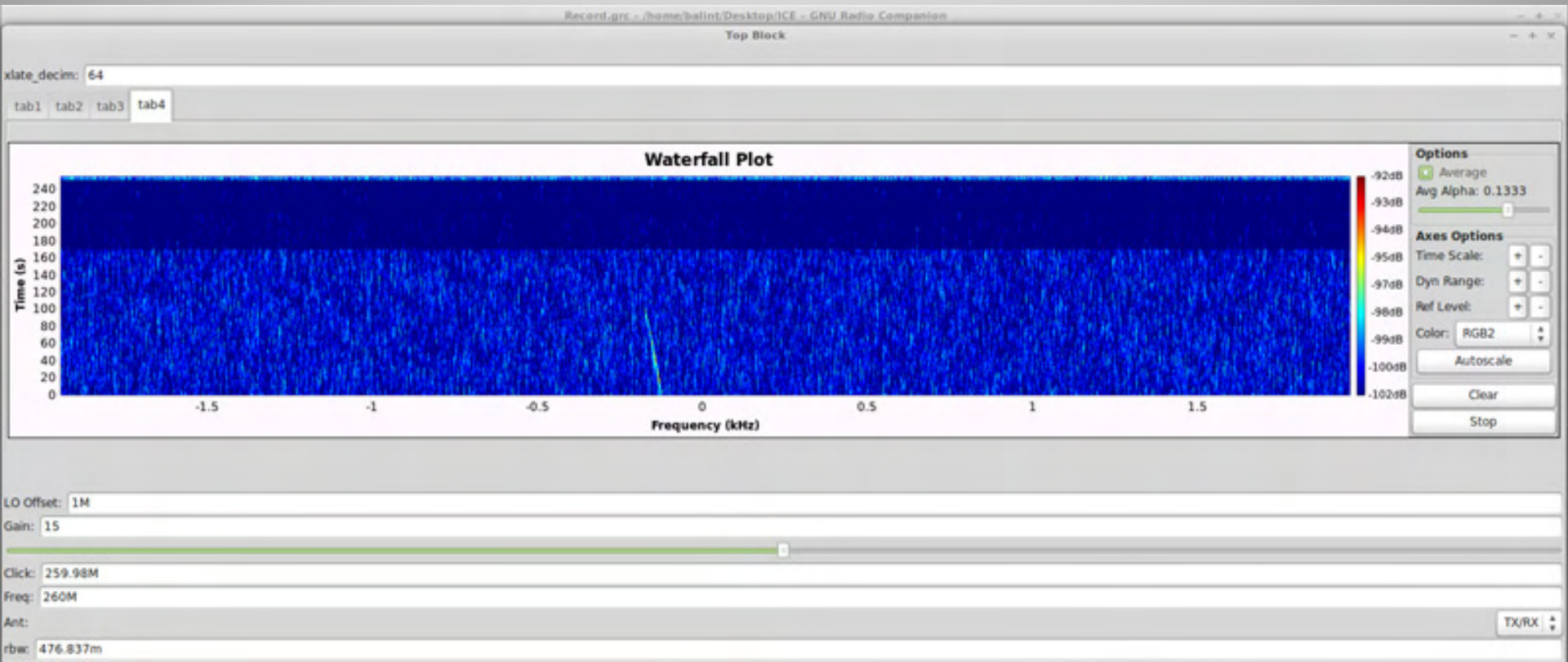
- Not your average 10 MHz/1 PPS
- Hydrogen Maser station reference
- Connected to each USRP

Display & Recording Flowgraph



Initial Transponder (Carrier) Detection

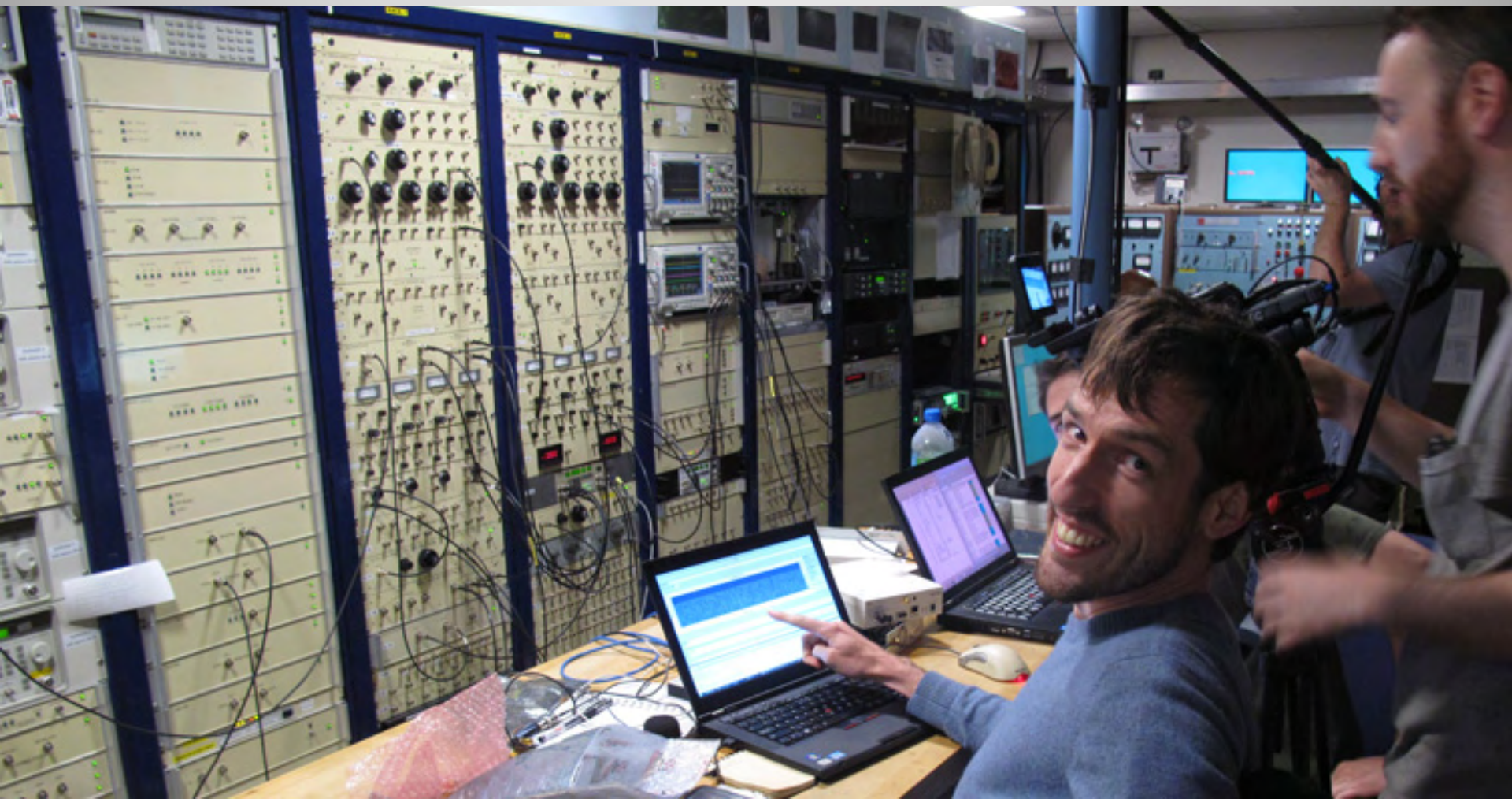
- C/N was lower than expected
- Ephemeris is stale (out-of-date)



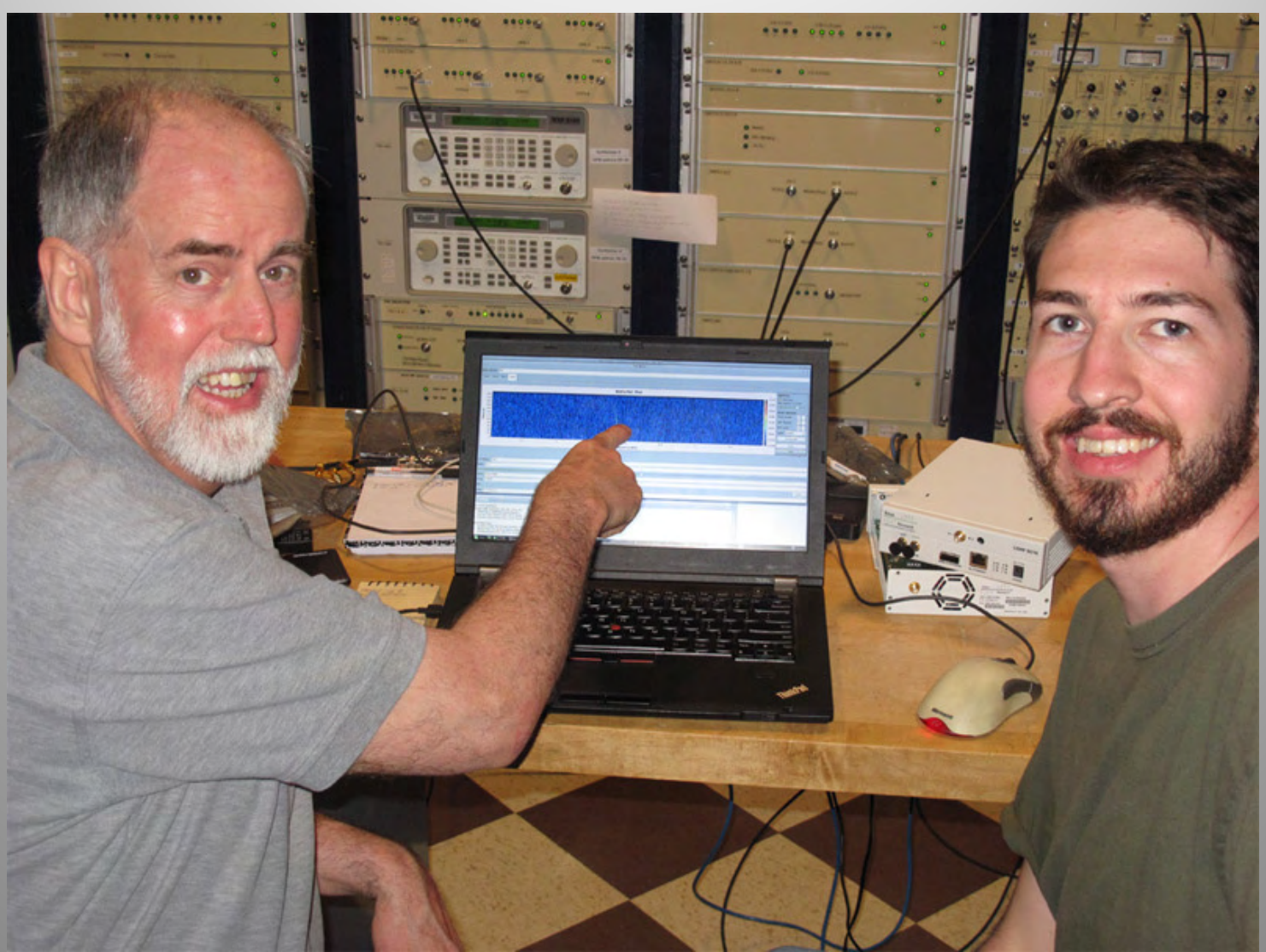
Stale Ephemeris

- Spacecraft has deviated from predicted path
  - Signal is being attenuated in beam's sidelobes
  - Requires manual sky search to find peak carrier signal
  - Done by one of the local gurus here (Phil Perillat):
    - Watching carrier peak move while tweaking pointing (quick)
    - Doing an automatic search around predicted point to maximise peak (longer)

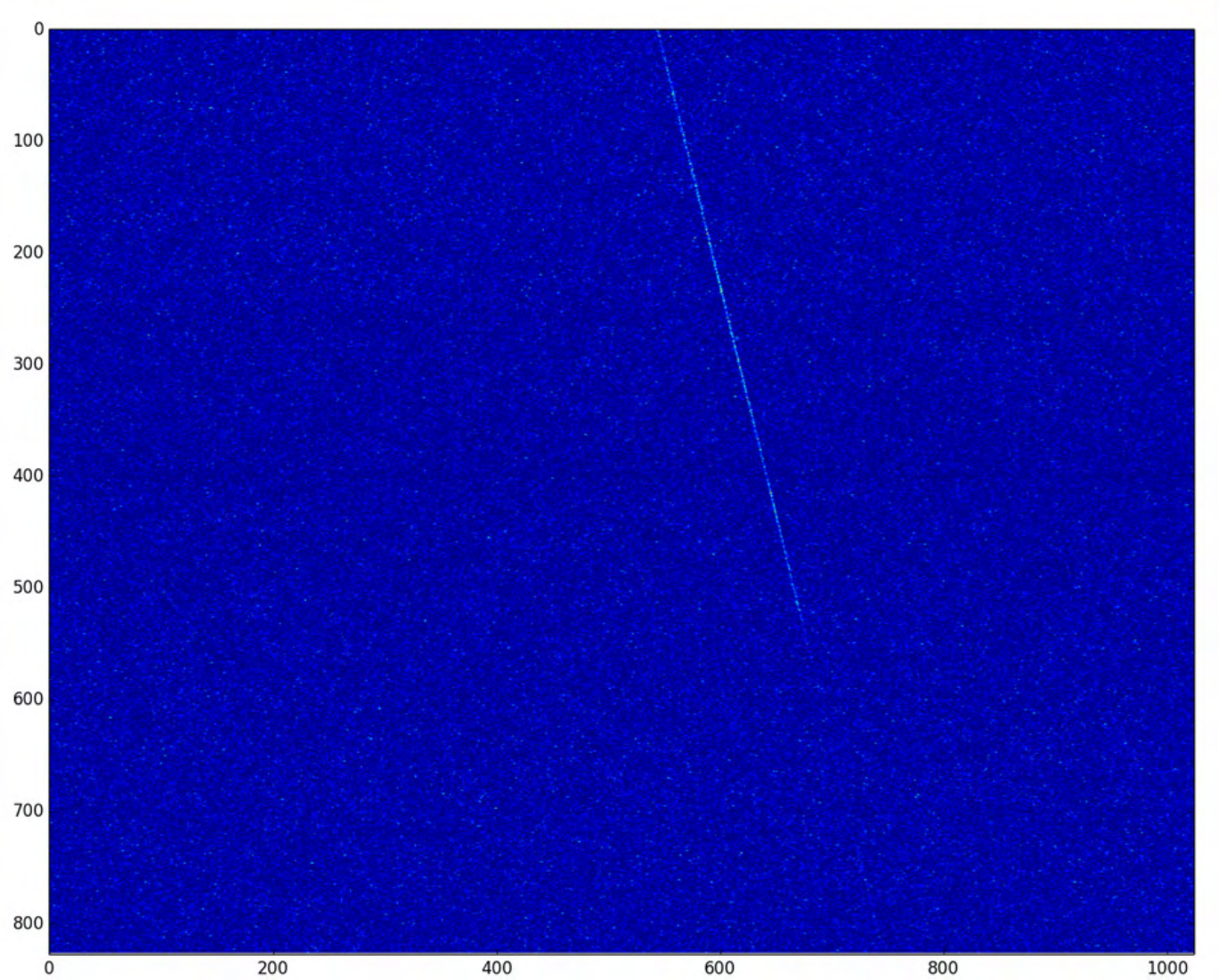
Still a good start…



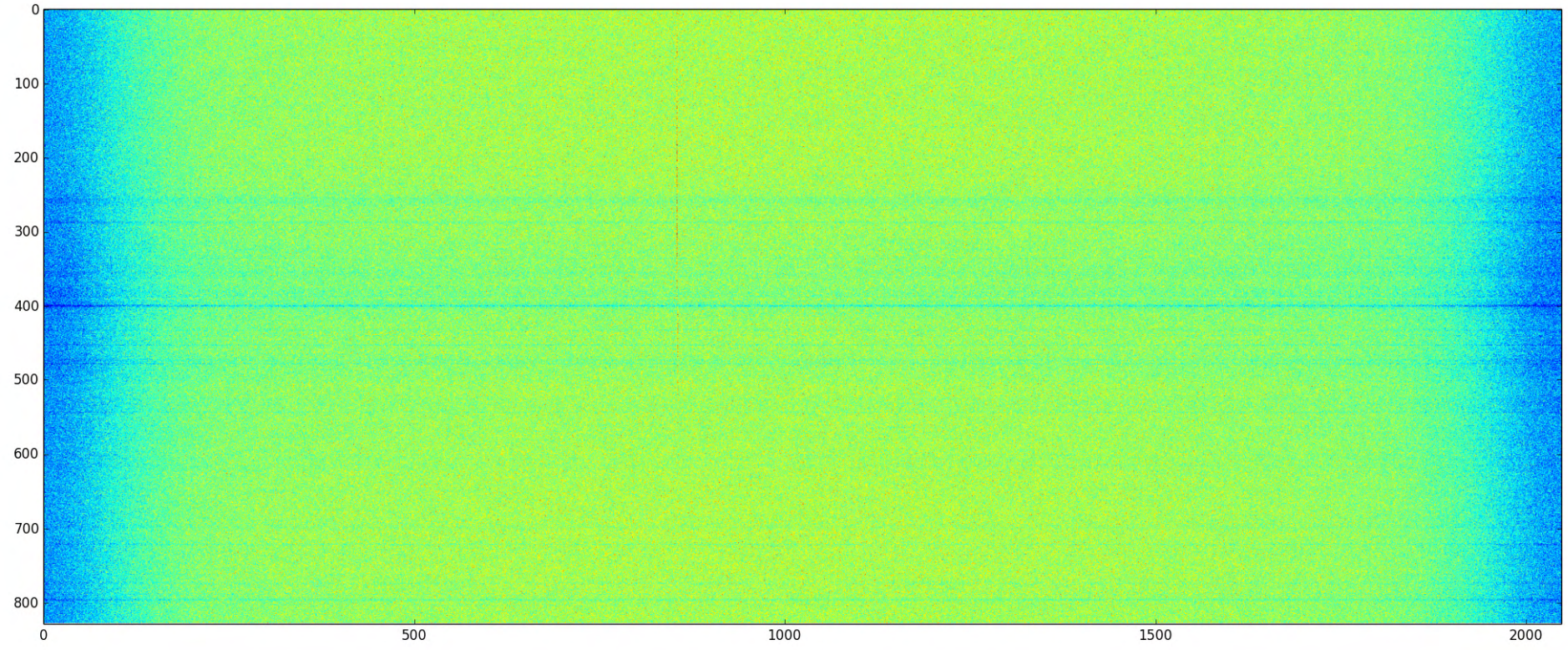
Still a good start…



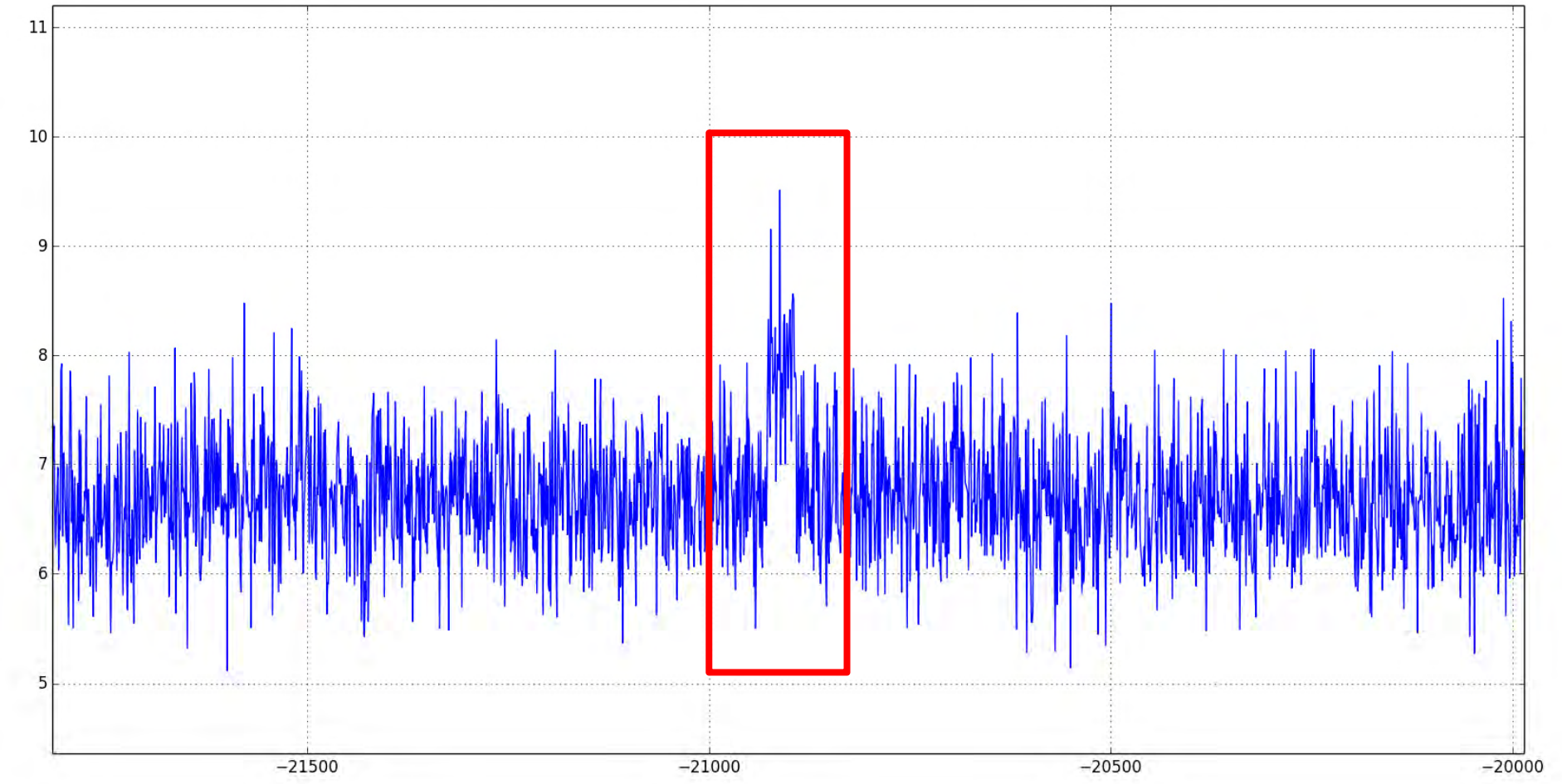
numpy & matplotlib



numpy & matplotlib

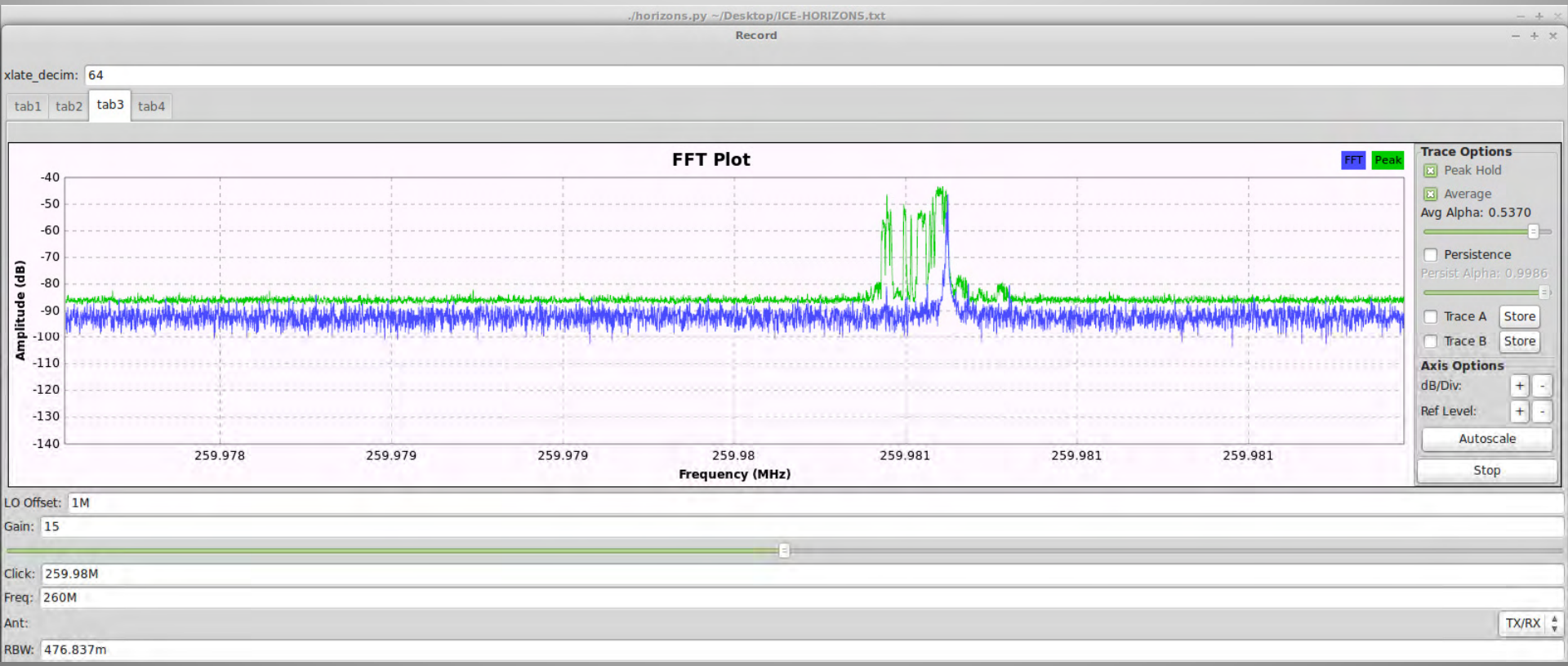


Weak Signal → Low RBW

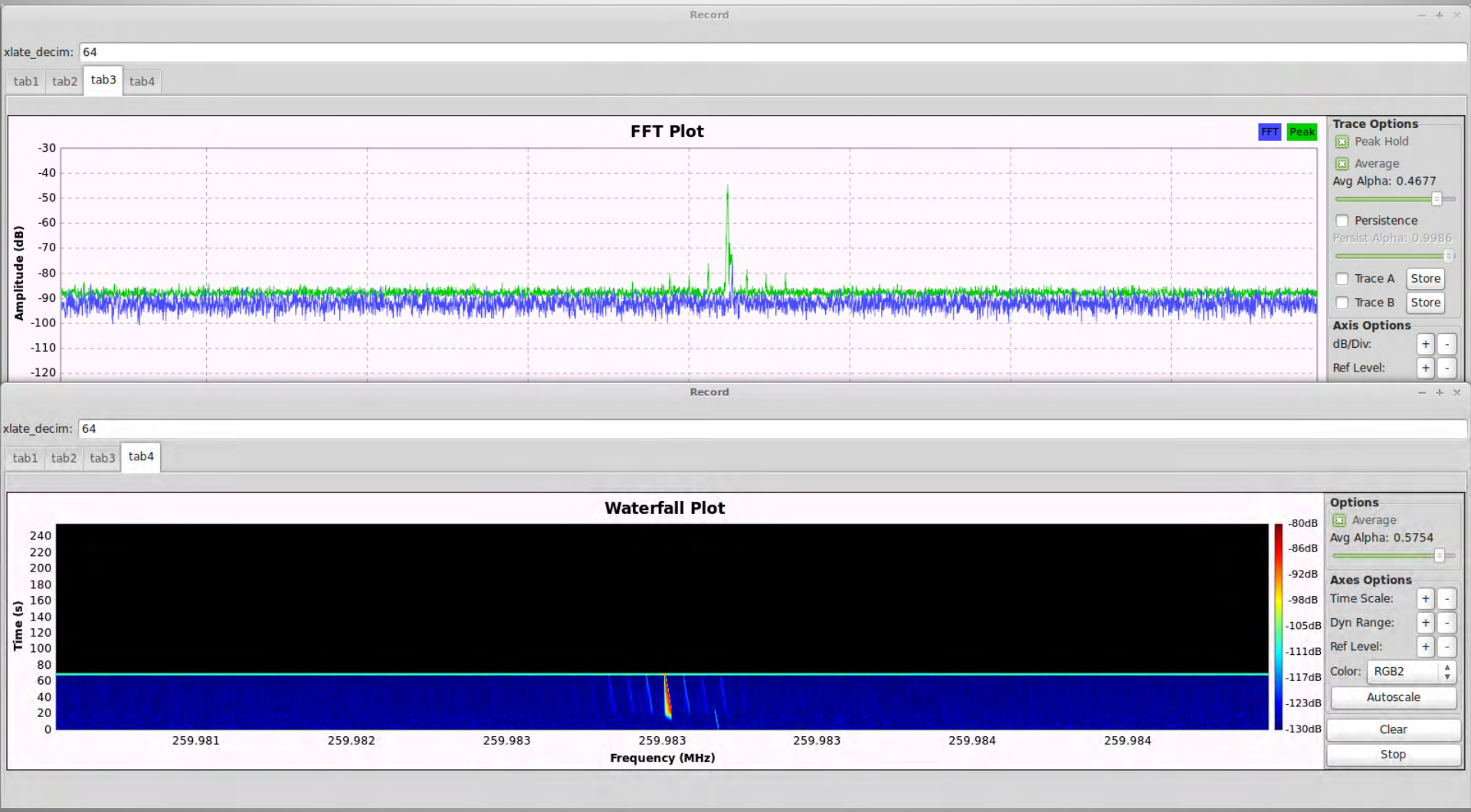


After Improving Pointing

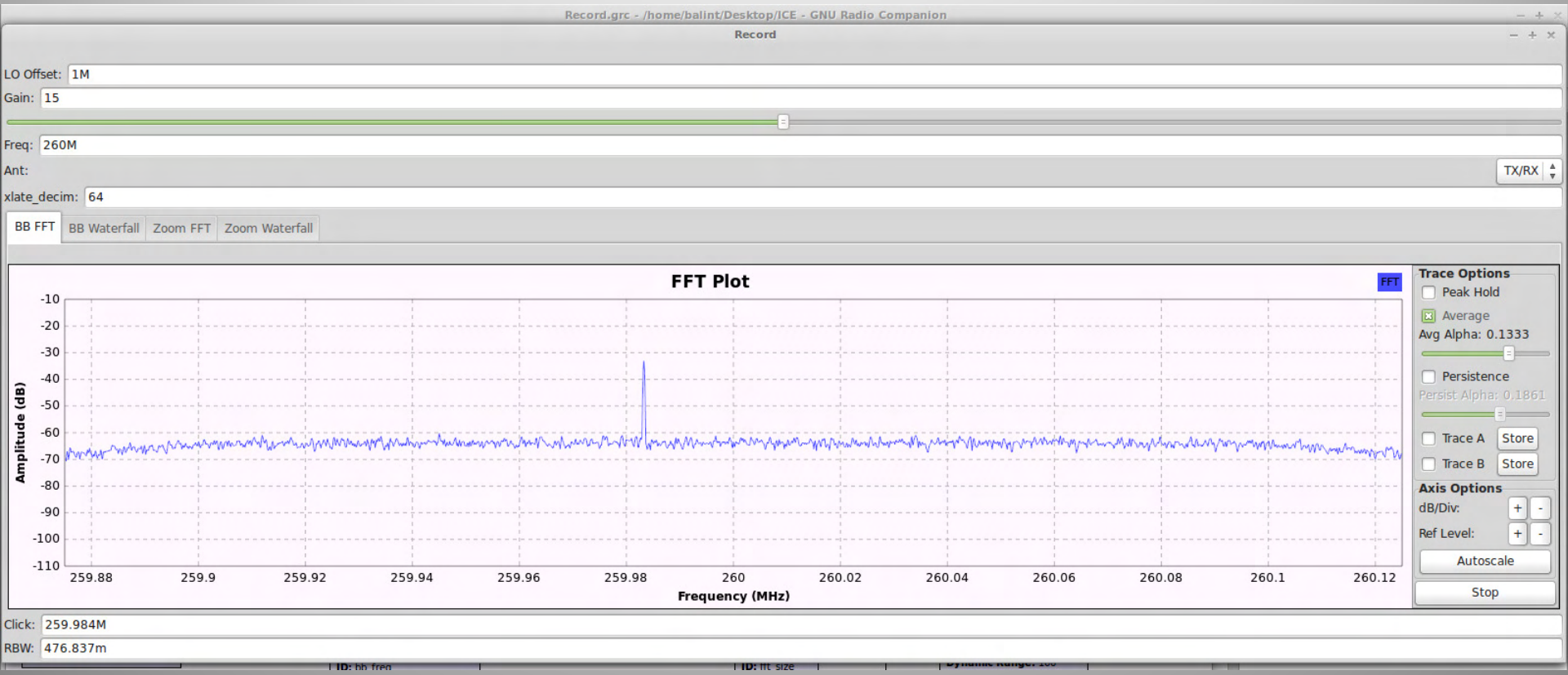
- ~45 dB C/N
- Moving peak below due to Doppler shift



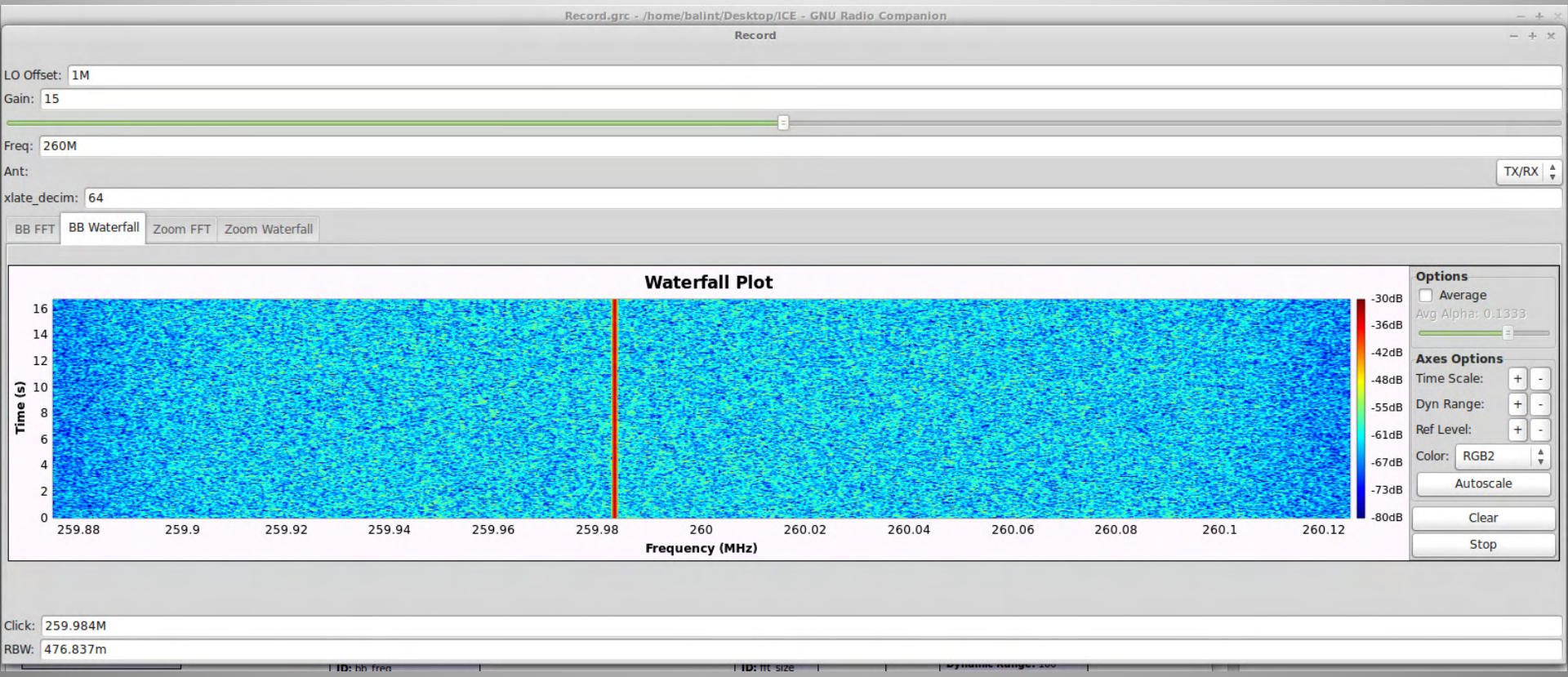
Dual Receive



Live Sampled Baseband

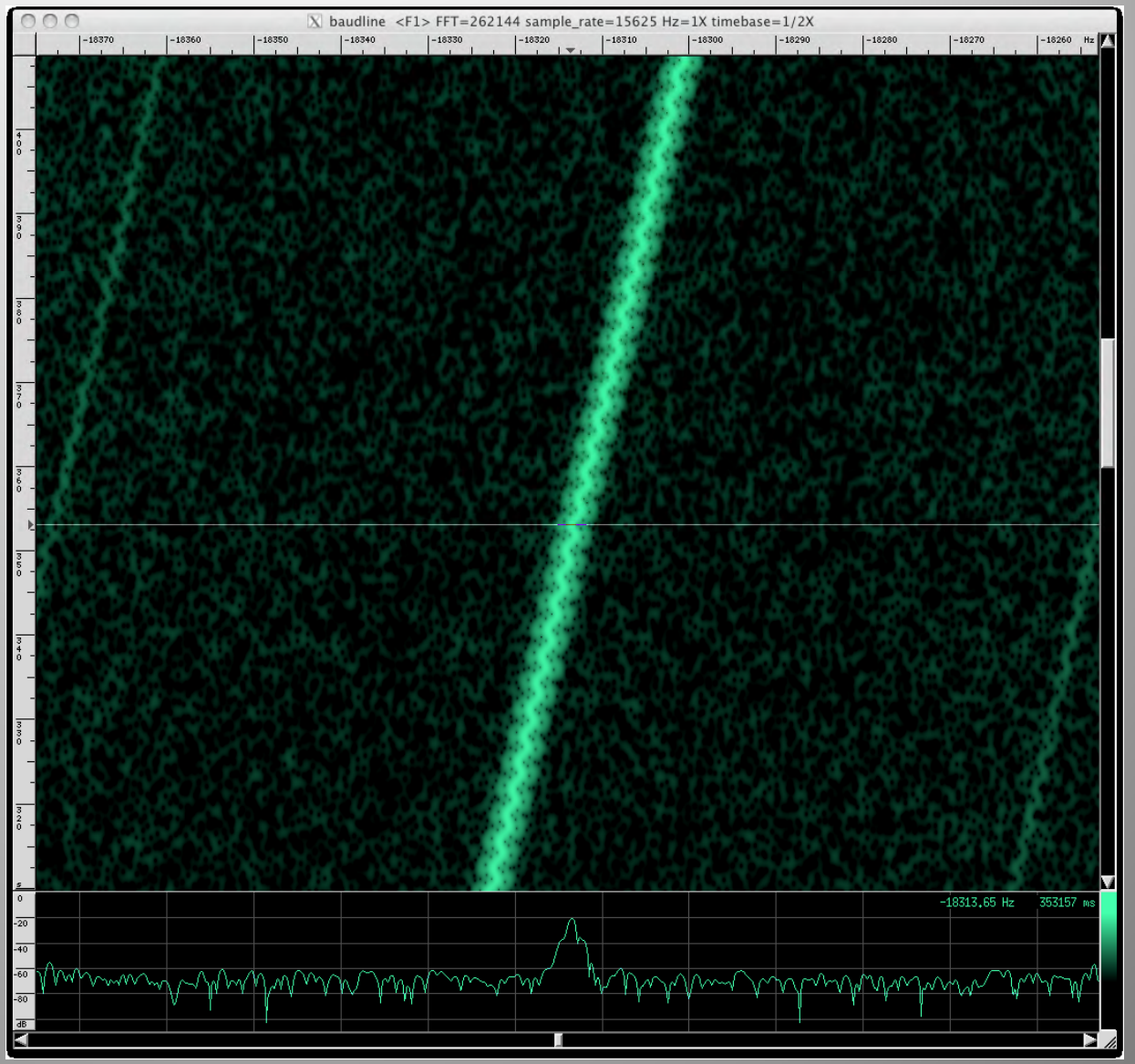


Live Sampled Baseband



Spin

- As space probe is spinning, so is antenna
- This can be seen at an extremely small RBW
- Image courtesy of Erik Olson (creator of ‘baudline’)

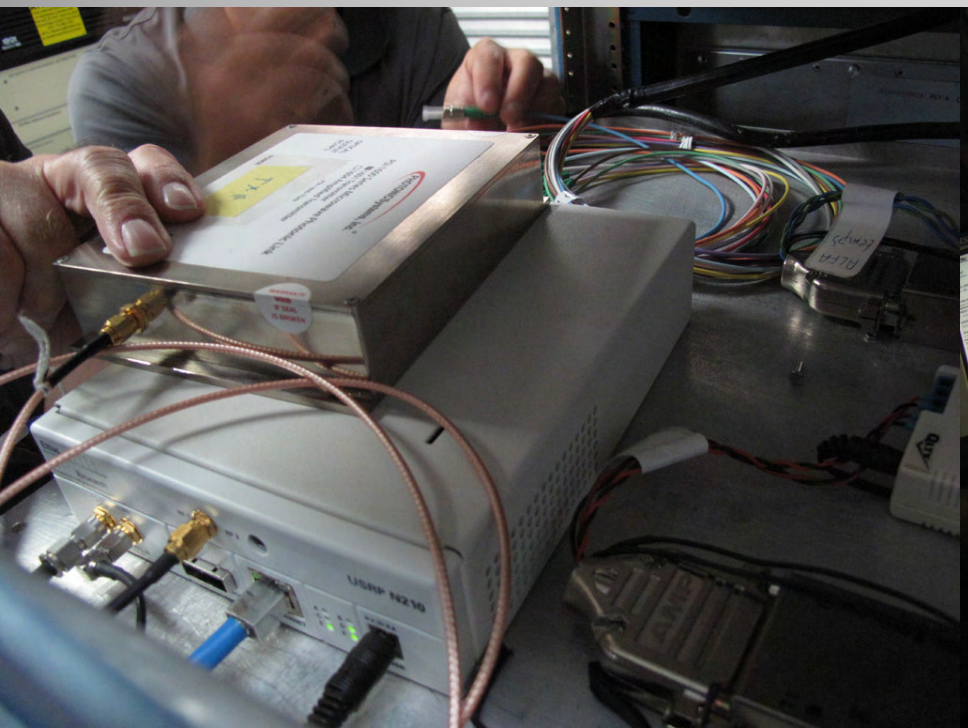


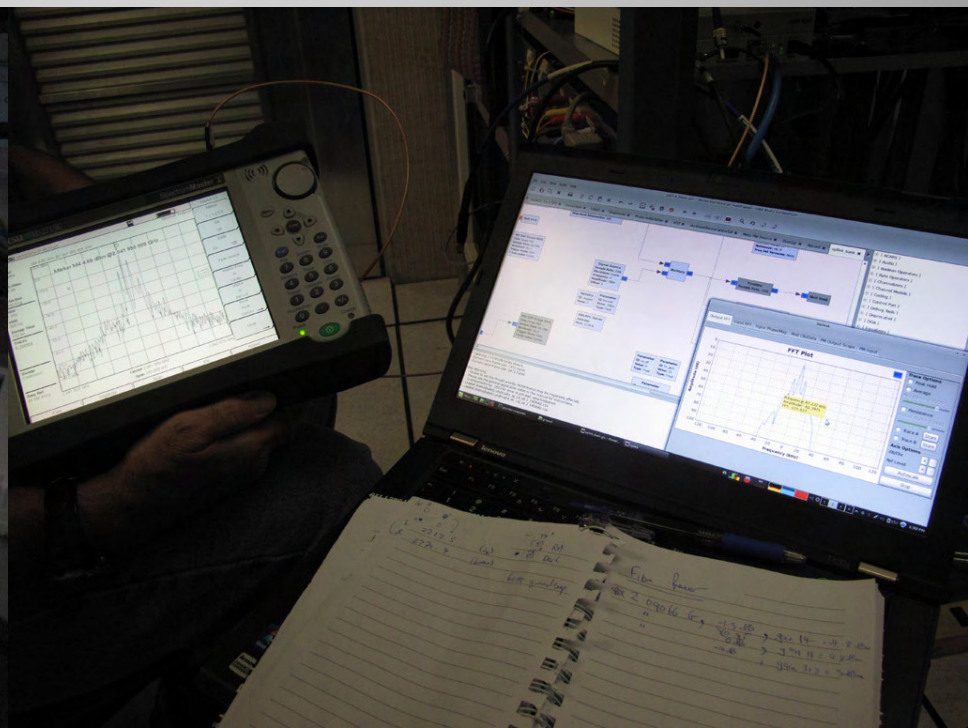
Media

- Wide-spread coverage
- #ISEE3, @ISEE3Reboot, @EttusResearch, @spenchdotnet
- This particular photo has appeared on The Register, CBS News…

Preparing for Uplink

- Dedicated TX USRP
- SBX daughterboard outputs RF into fiber link
  - RF-over-fiber sent to dome (to pre-amps & PA)

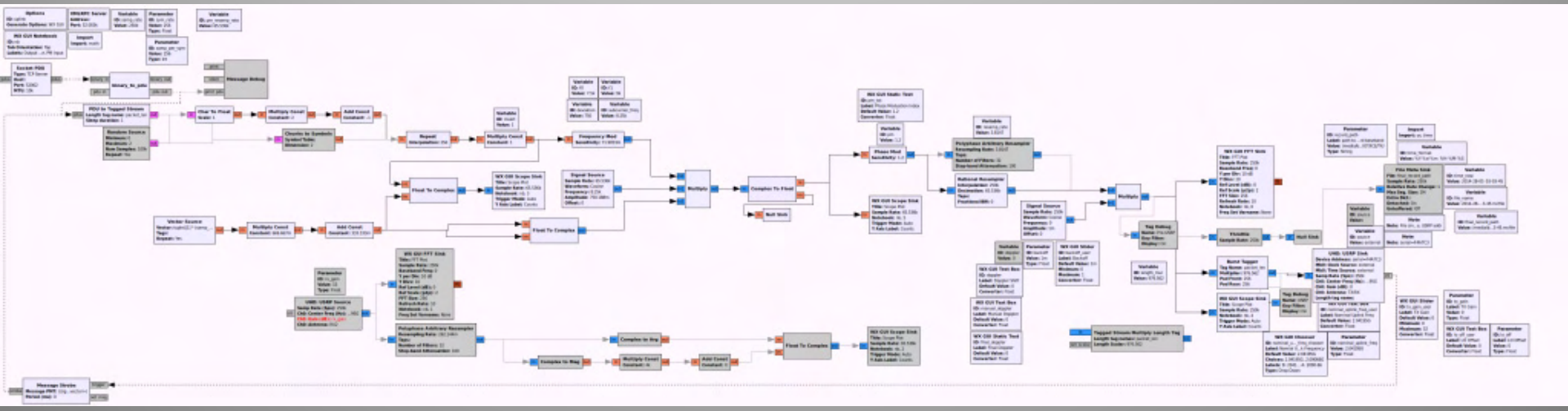




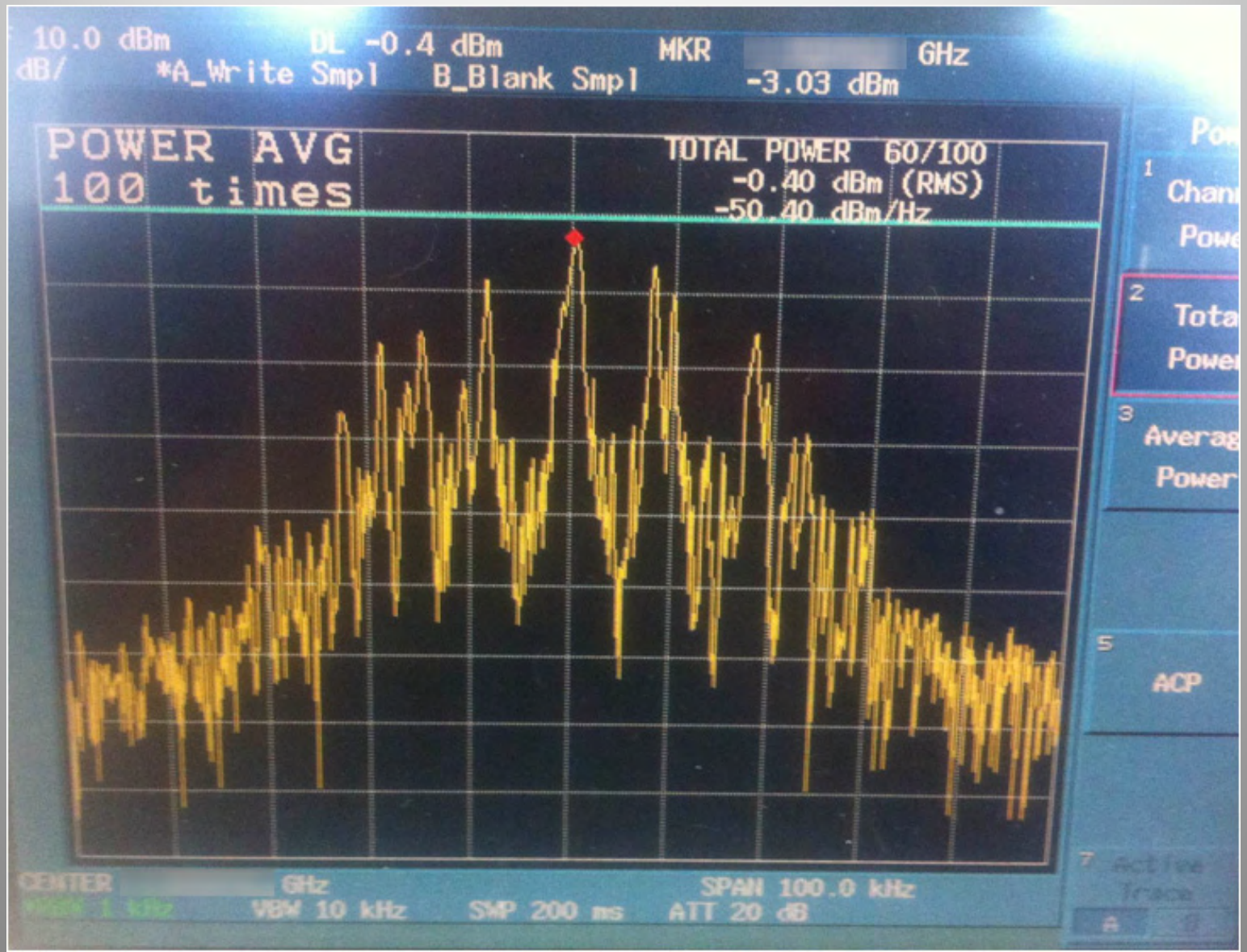
Preparing for Uplink

Uplink GNU Radio App

- Created with John Malsbury (@_jmalsbury)
- Command bit strings sent via Socket PDU
- Parameters via XML-RPC



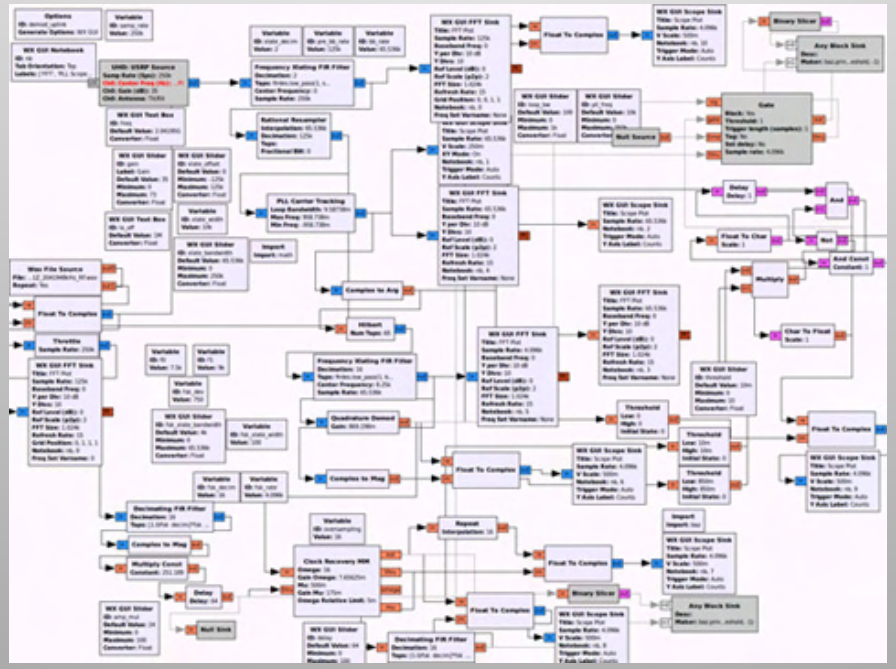
Previous Test at Ettus HQ (NISV)



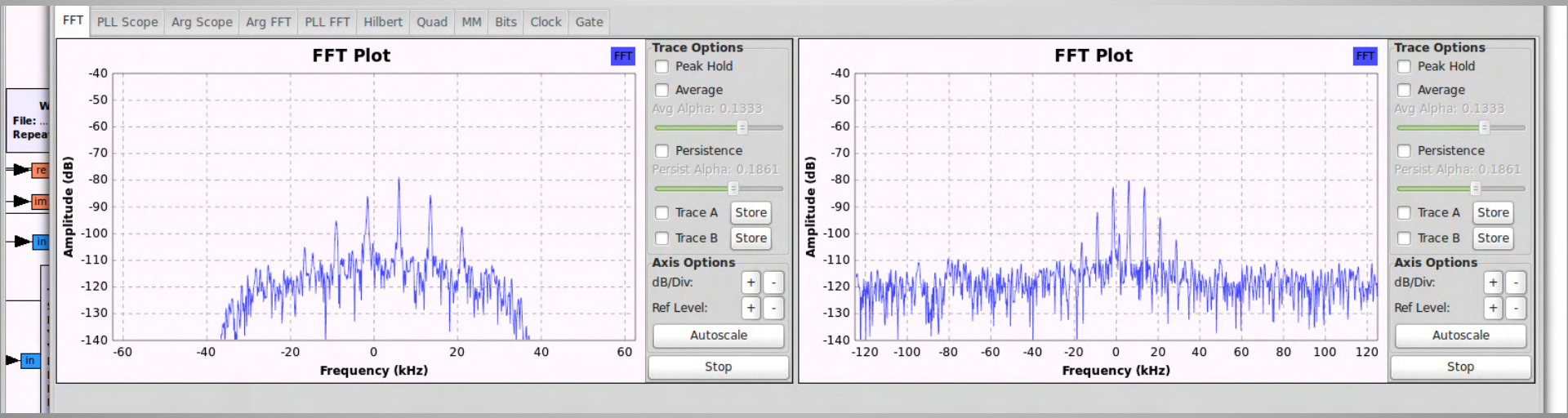
Fingers Crossed

- Some ambiguity remains
  - Not all modulation/protocol details completely described in documents
  - Run through possible permutations of parameters to ensure all combinations
    - Double-checking that commands cannot misinterpreted (e.g. fire thrusters instead of enabling telemetry)
- Created a test uplink demodulator
  - Identical bits decoded
  - Assuming same mistake is not on both sides

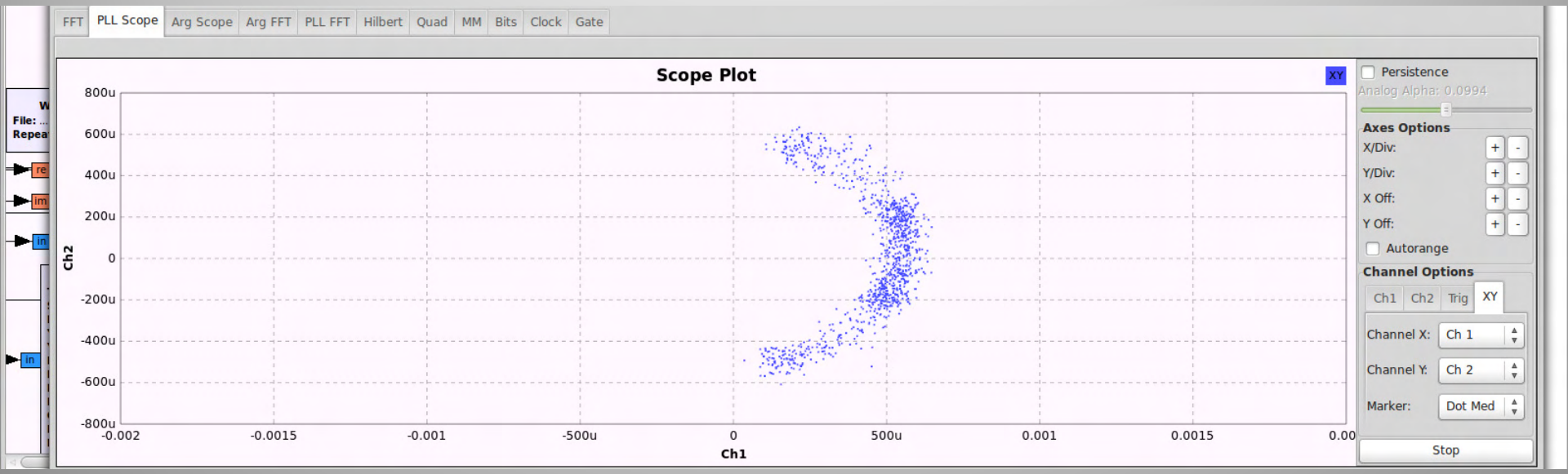
Verifying Transmitted (Test) Data



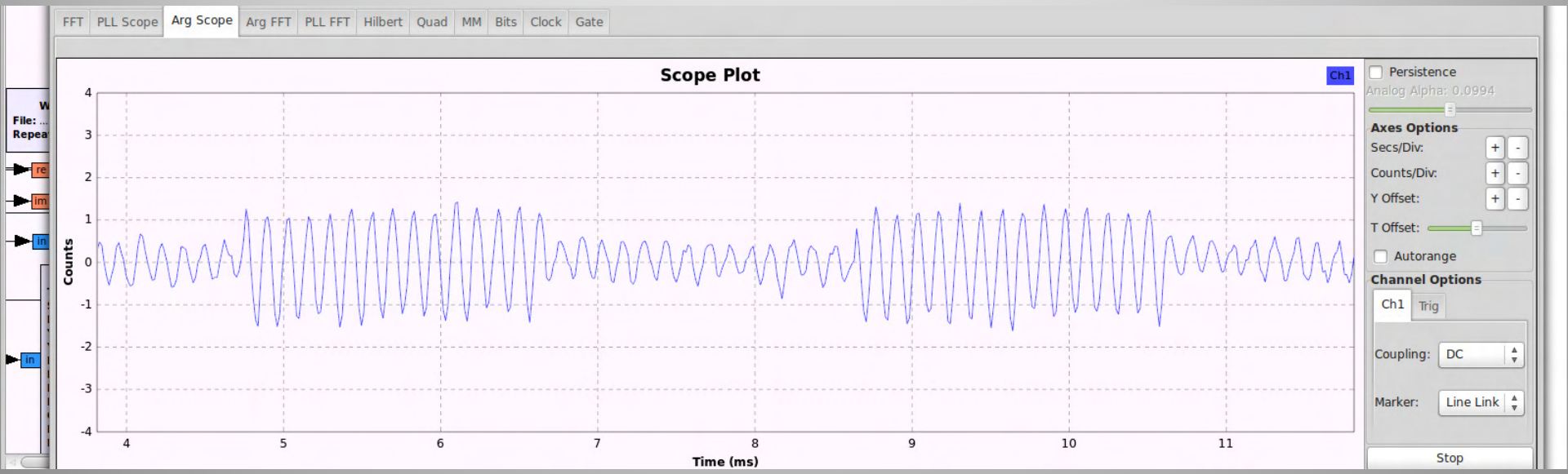
Received Test Uplink Signal



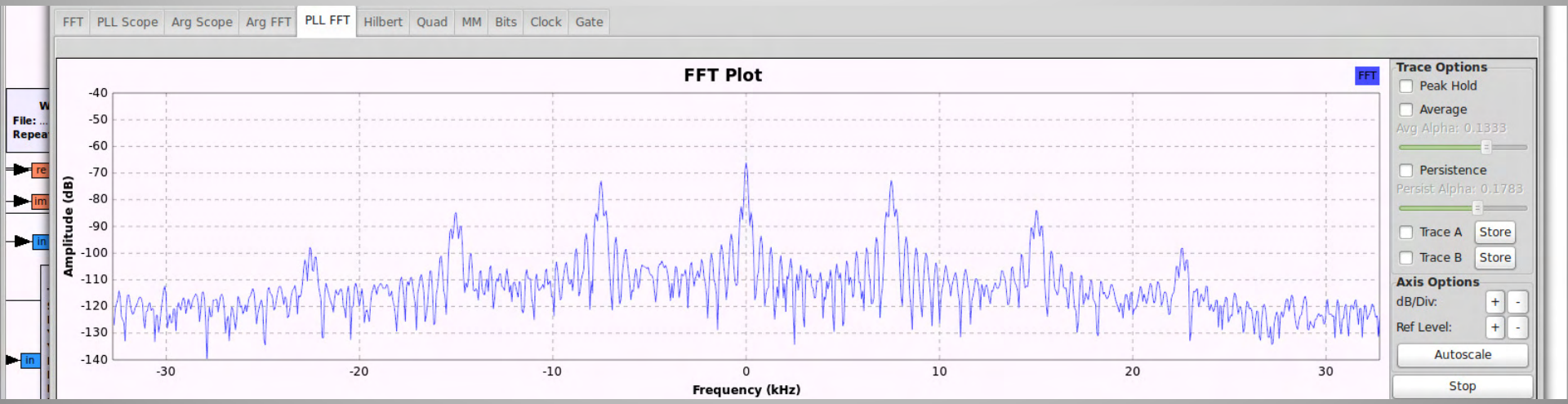
IQ Scope Plot



Phase Demodulated Signal



Phase Demodulated Signal



Self-clocking Signal

Receiver Clock Recovery

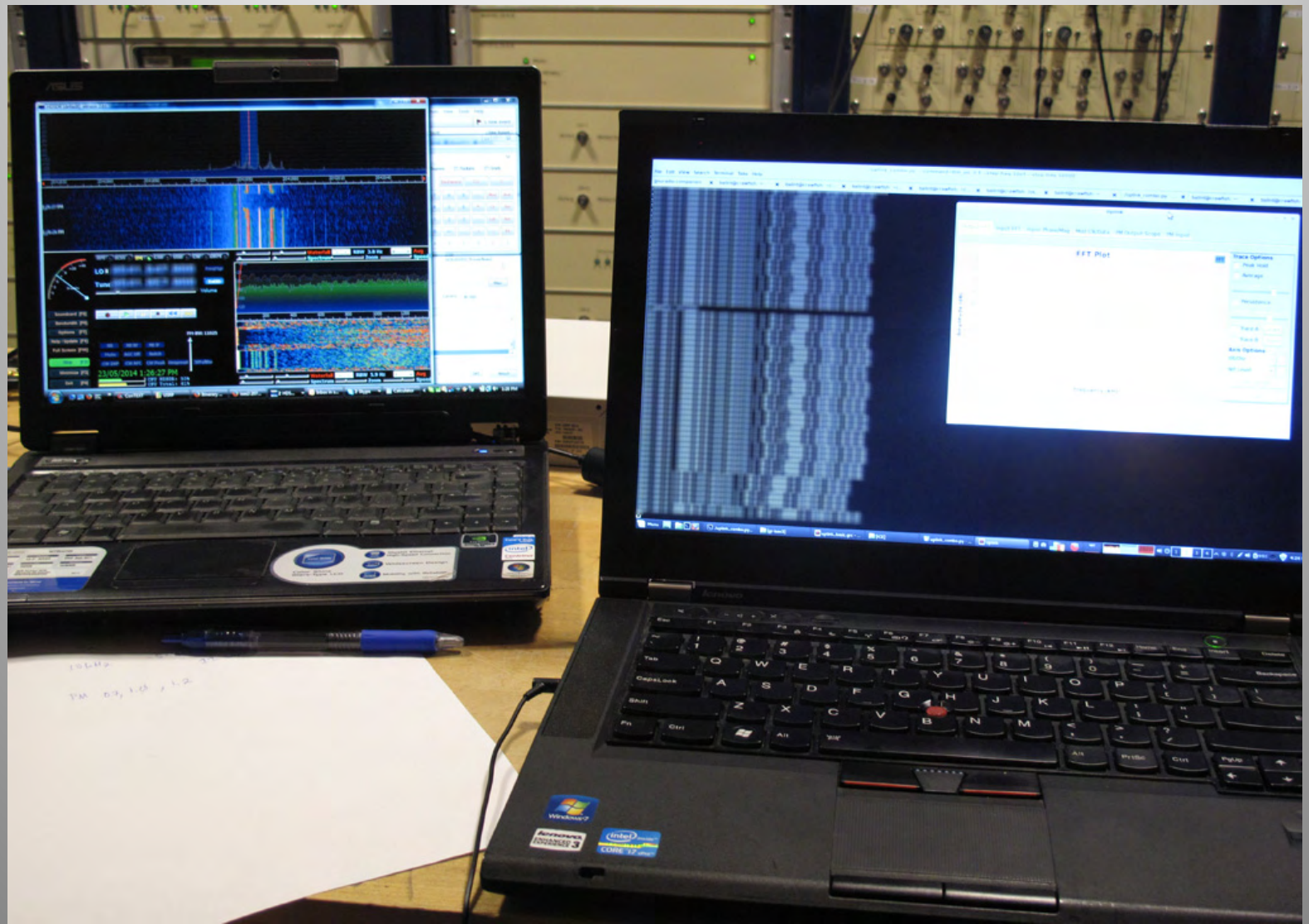
Self-clocked Sampling

Telemetry

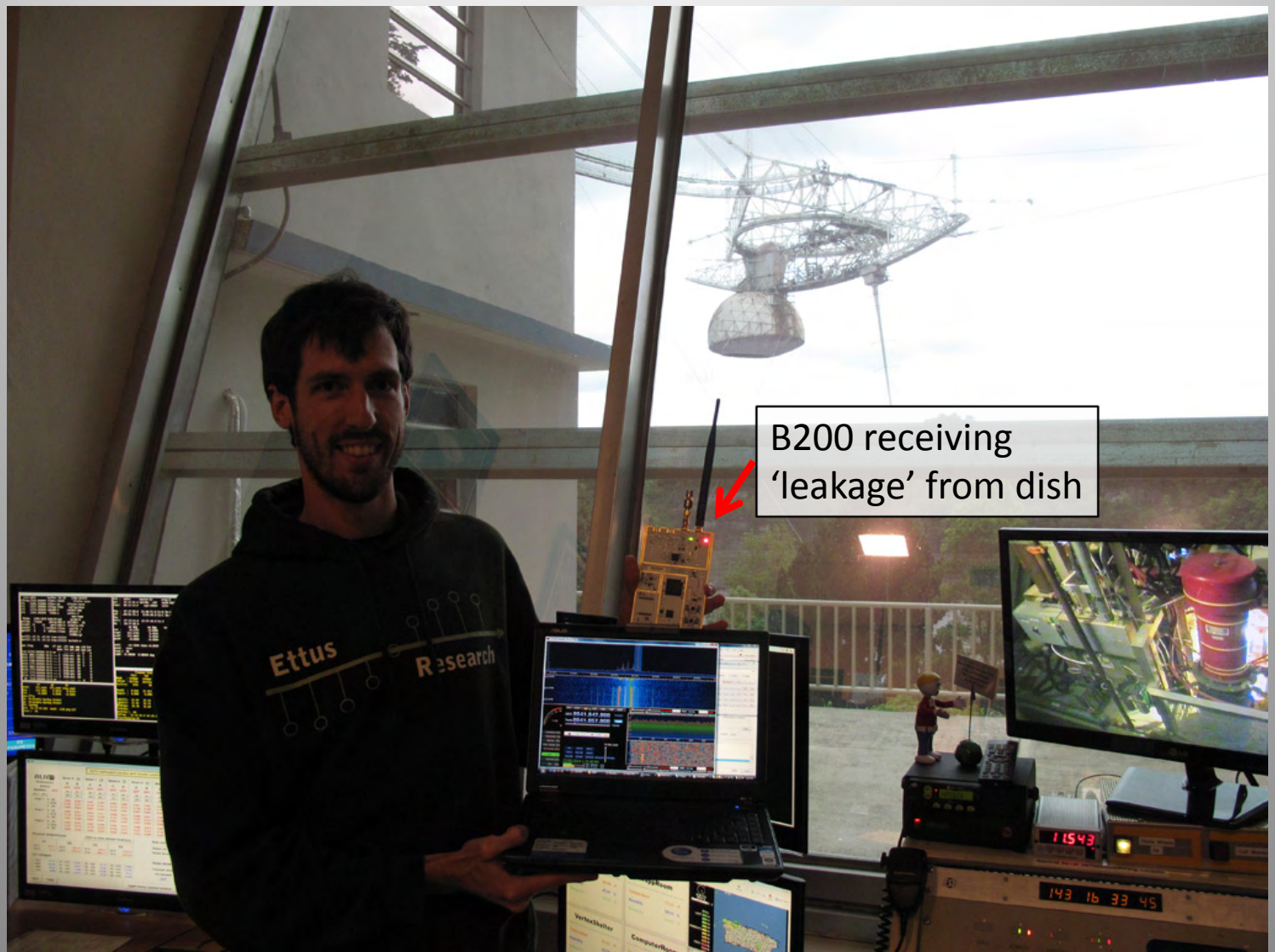
- Telemetry can be downlinked at a variety of different bit rates
- Convolutionally encoded
  - K=24
  - ½ rate
  - Quick-Look-In code
- “Nonsystematic Convolutional Codes for Sequential Decoding in Space Applications” – Massey & Costello

Fingers Crossed

Transmission to Enable Telemetry



Verifying Transmitted Signal

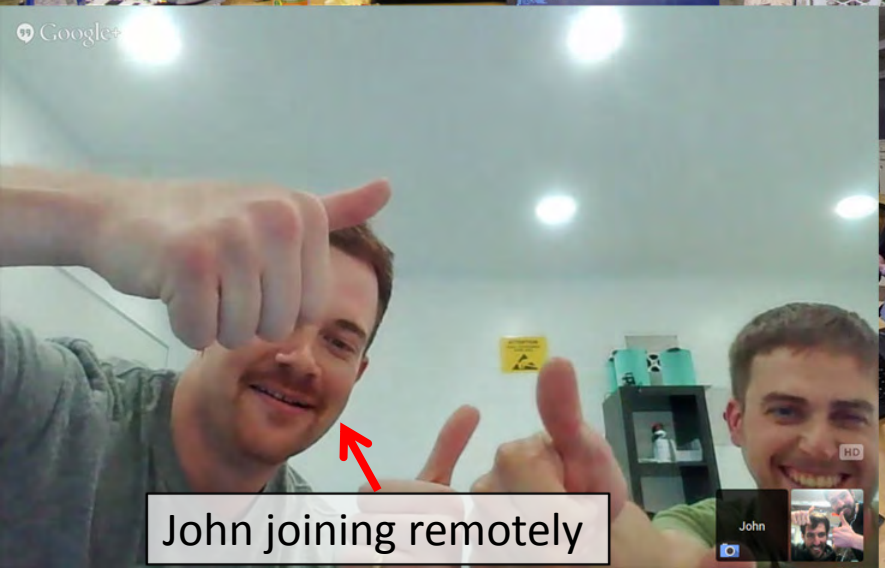


We Have Telemetry!

Turned out that all interpretations & assumptions were valid, so it wasn't necessary to run all the permutations

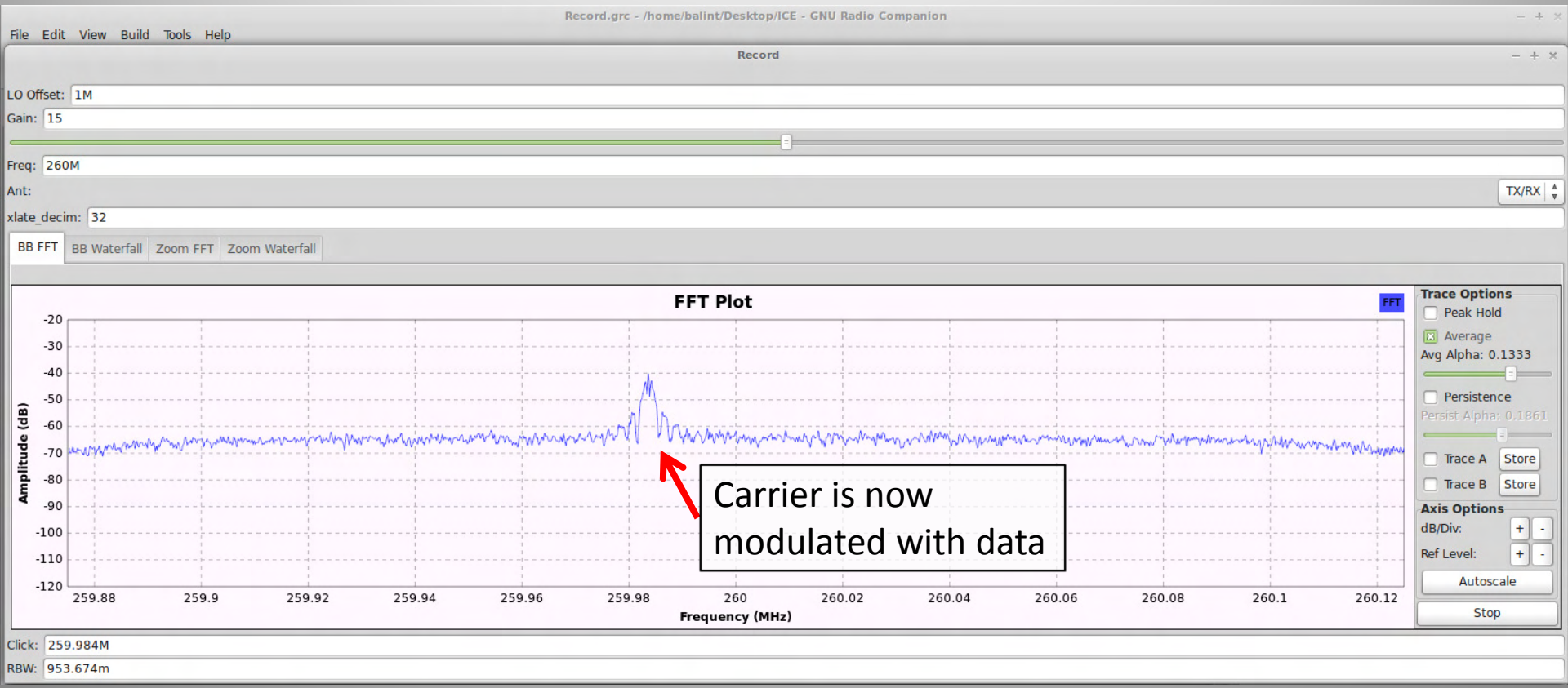
Celebration

Phil Perillat: lives and breathes the telescope

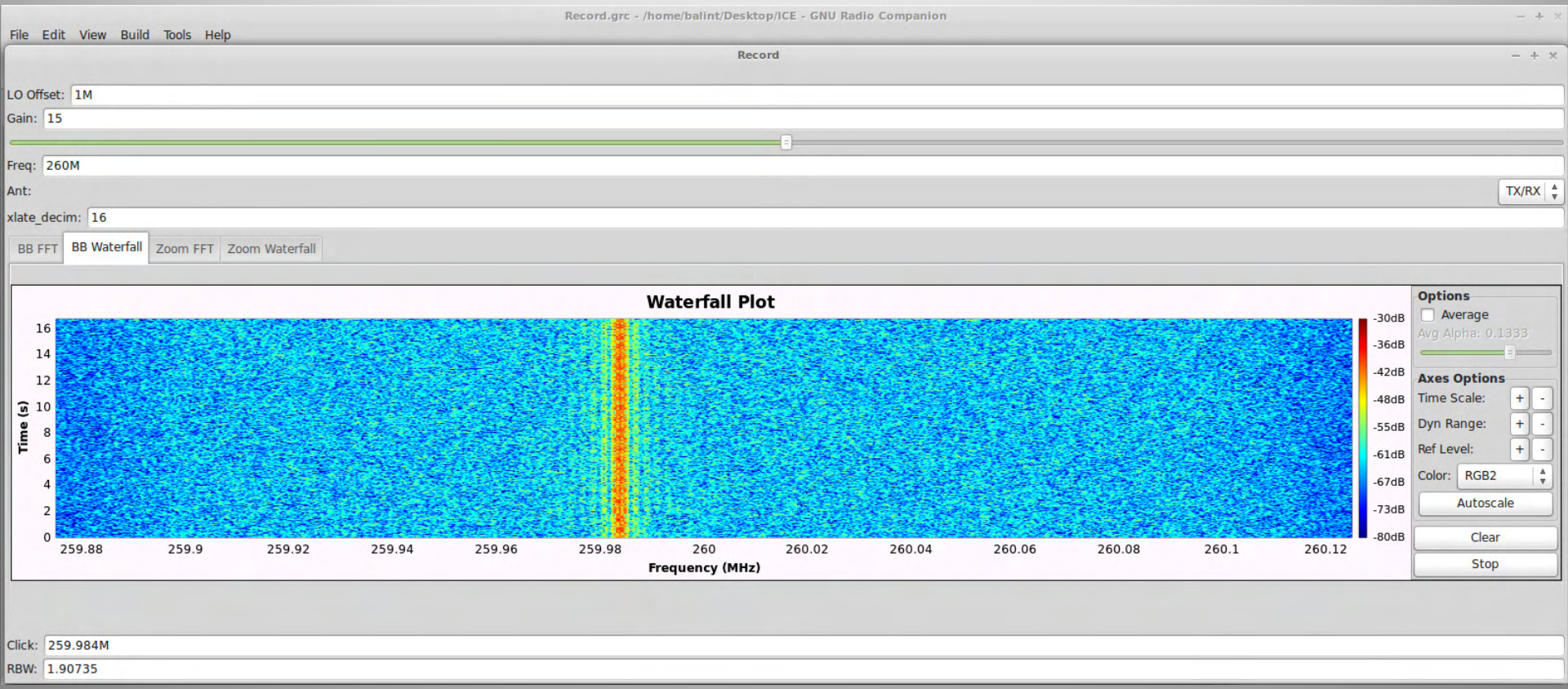


John joining remotely

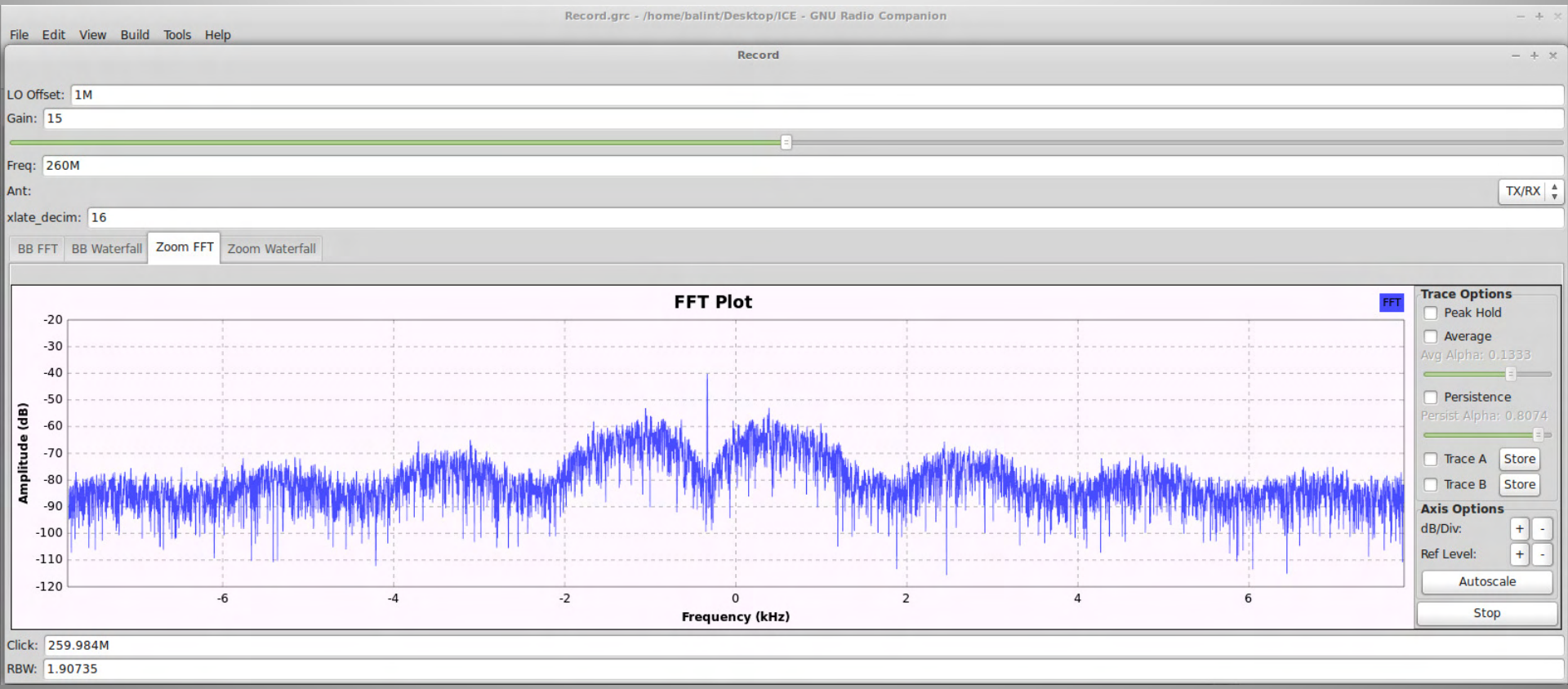
Live Sampled Baseband



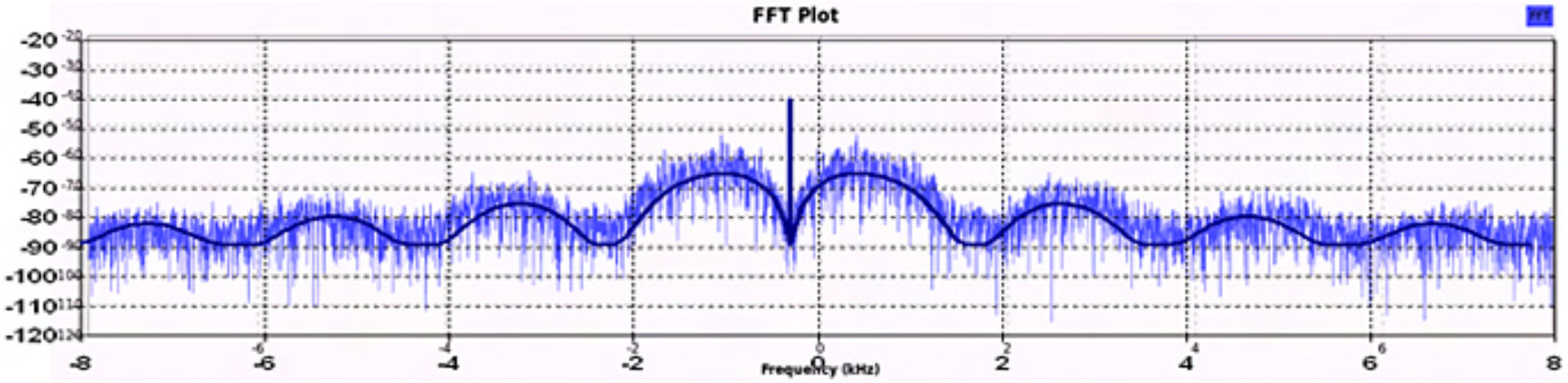
Live Sampled Baseband



Zoomed Baseband



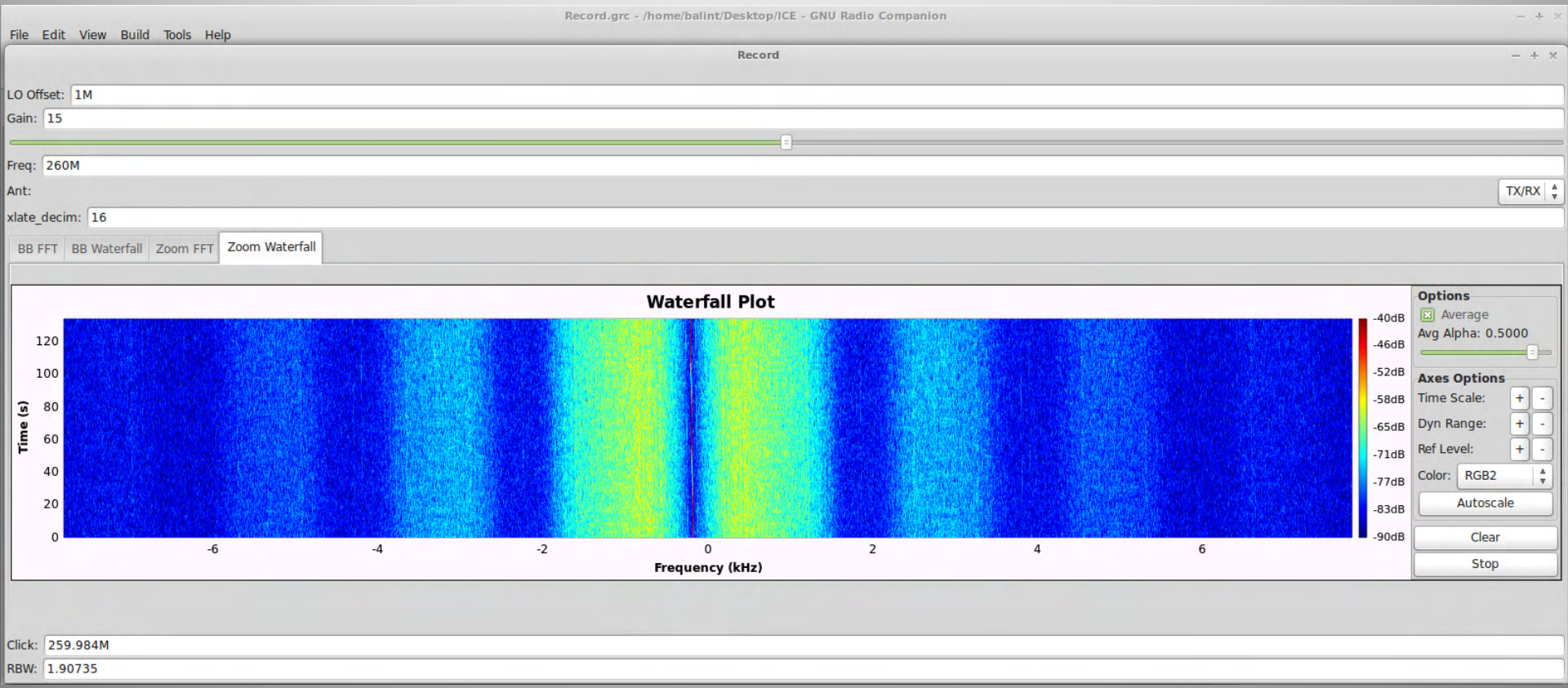
Compare to Simulation



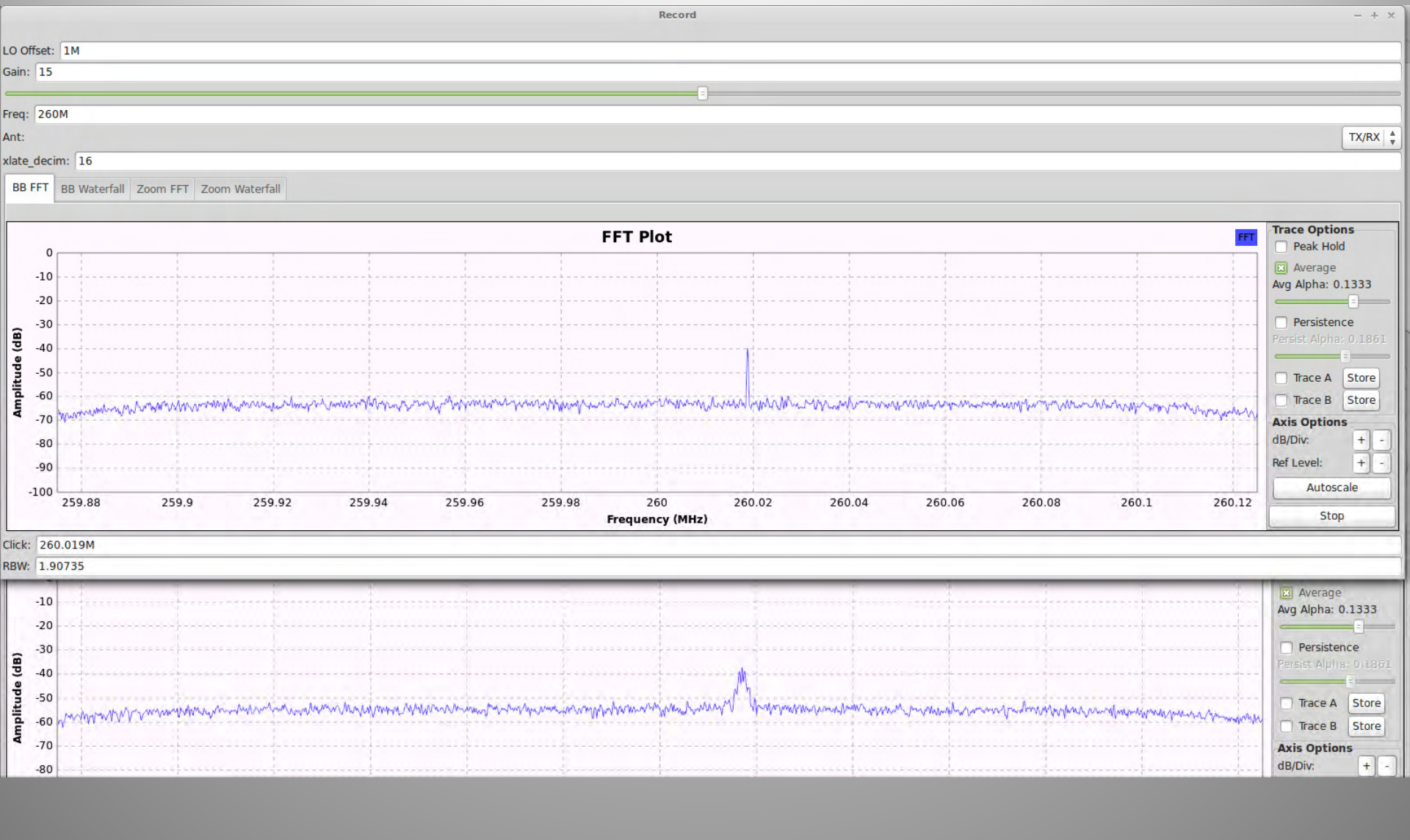
assumptions:
512 bps, R=1/2 convolutional code
biphase PSK, 60 deg mod index
free parameters:
noise power, total signal power, frequency offset

measured spectrum by ISEE-3 Reboot Project
simulated spectrum by. A. Vollhardt (DH2VA), AMSAT-DL

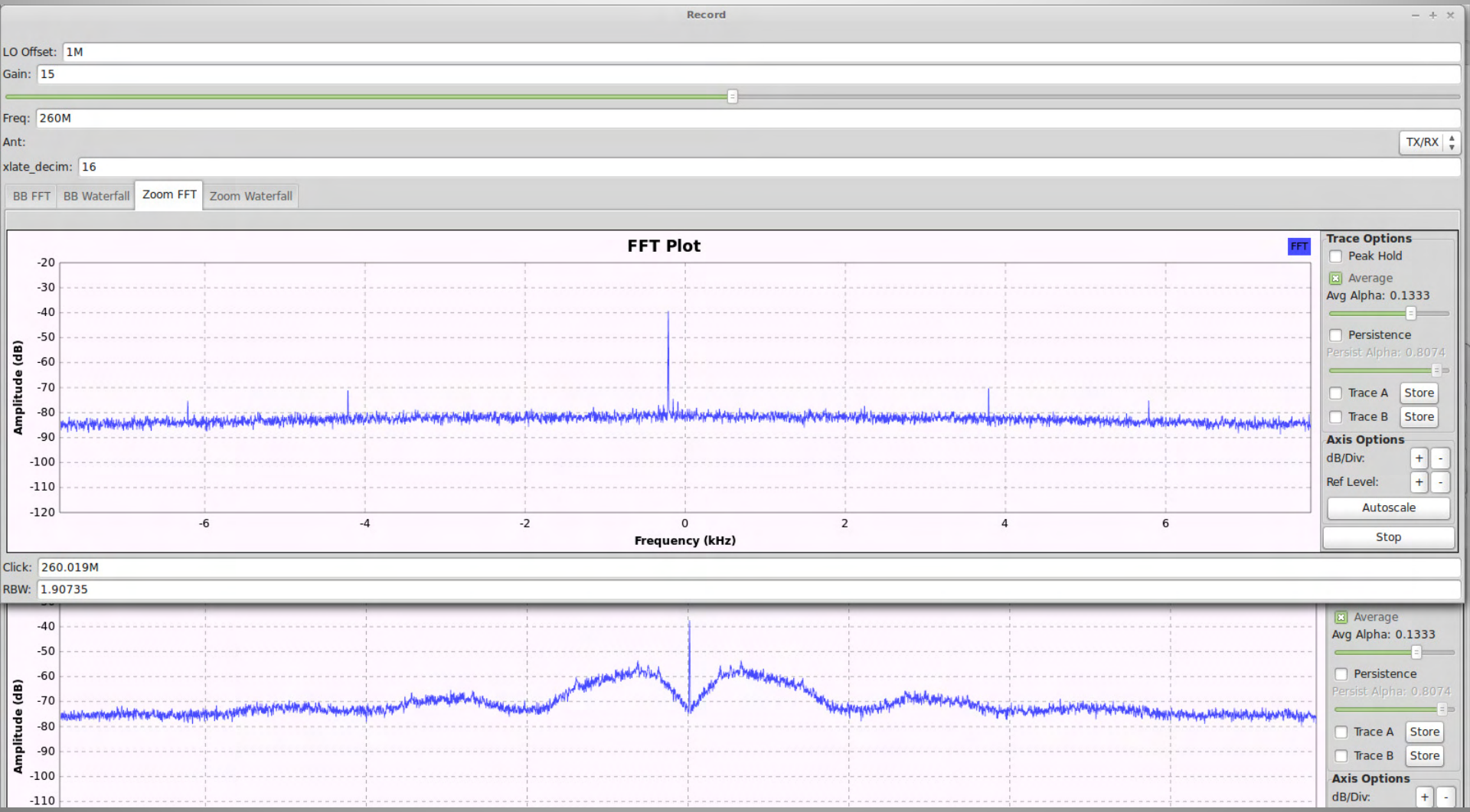
Zoomed Baseband



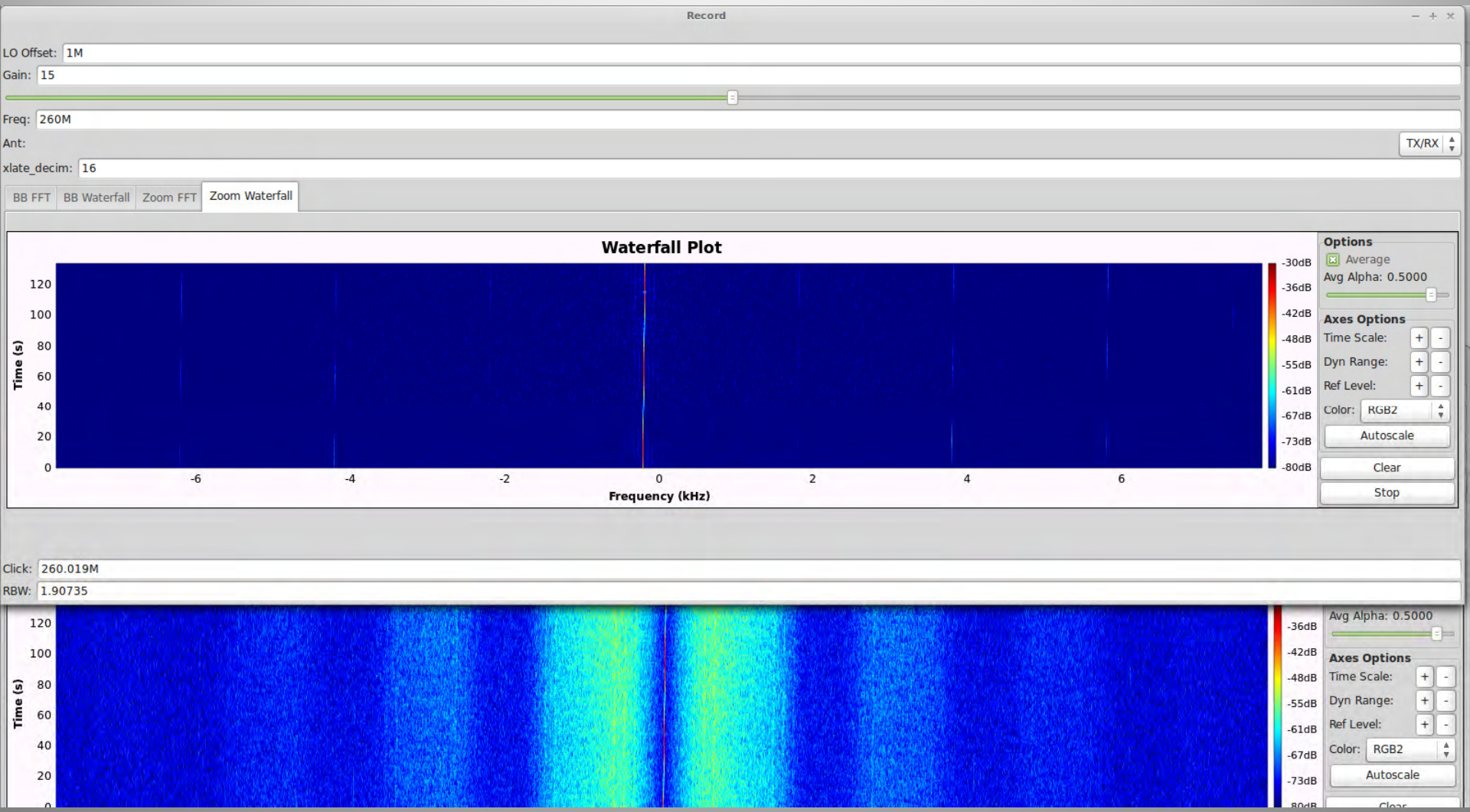
Only carrier on B, TLM on A



Zoomed: Only carrier on B, TLM on A



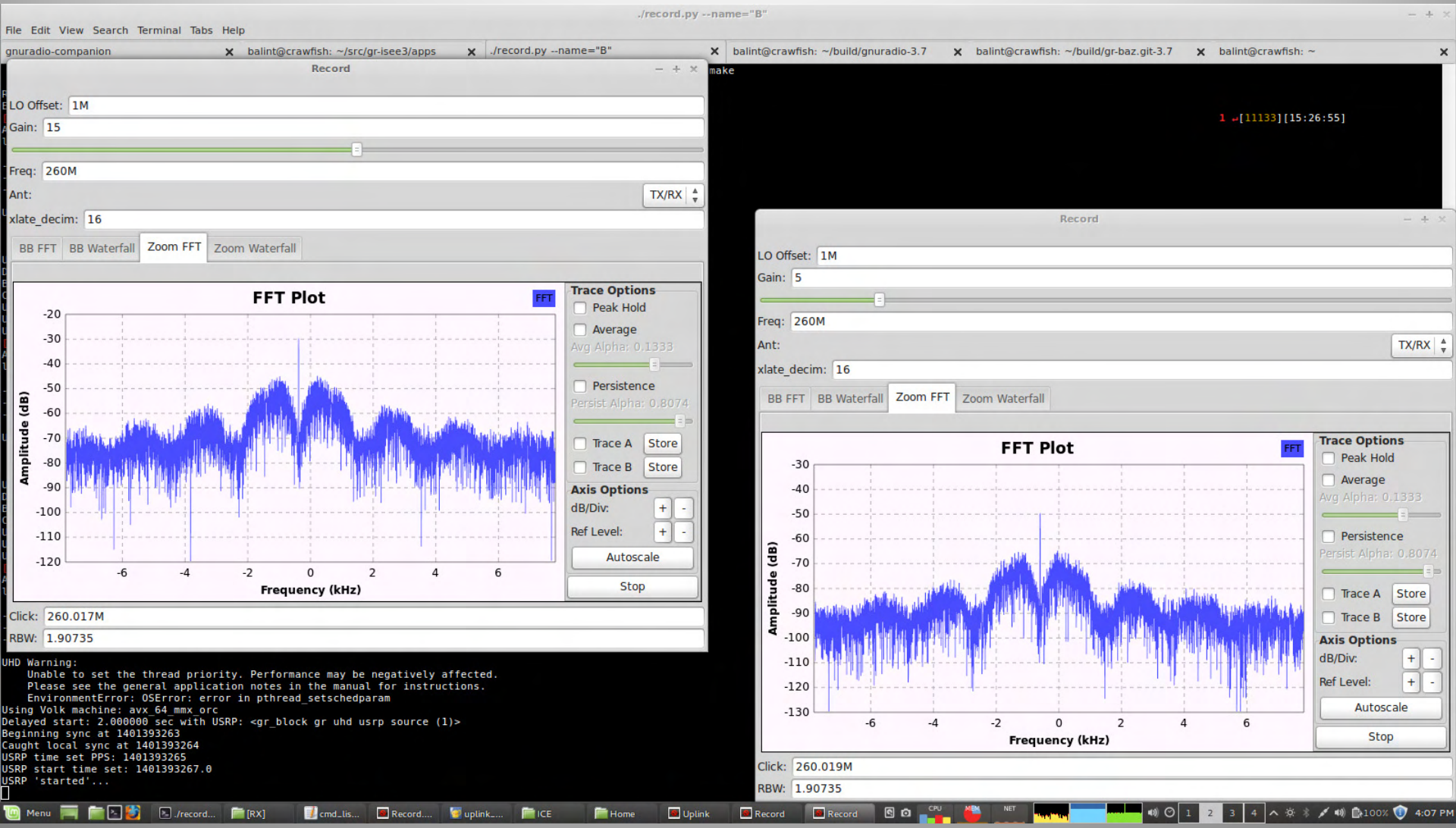
Only carrier on B, TLM on A



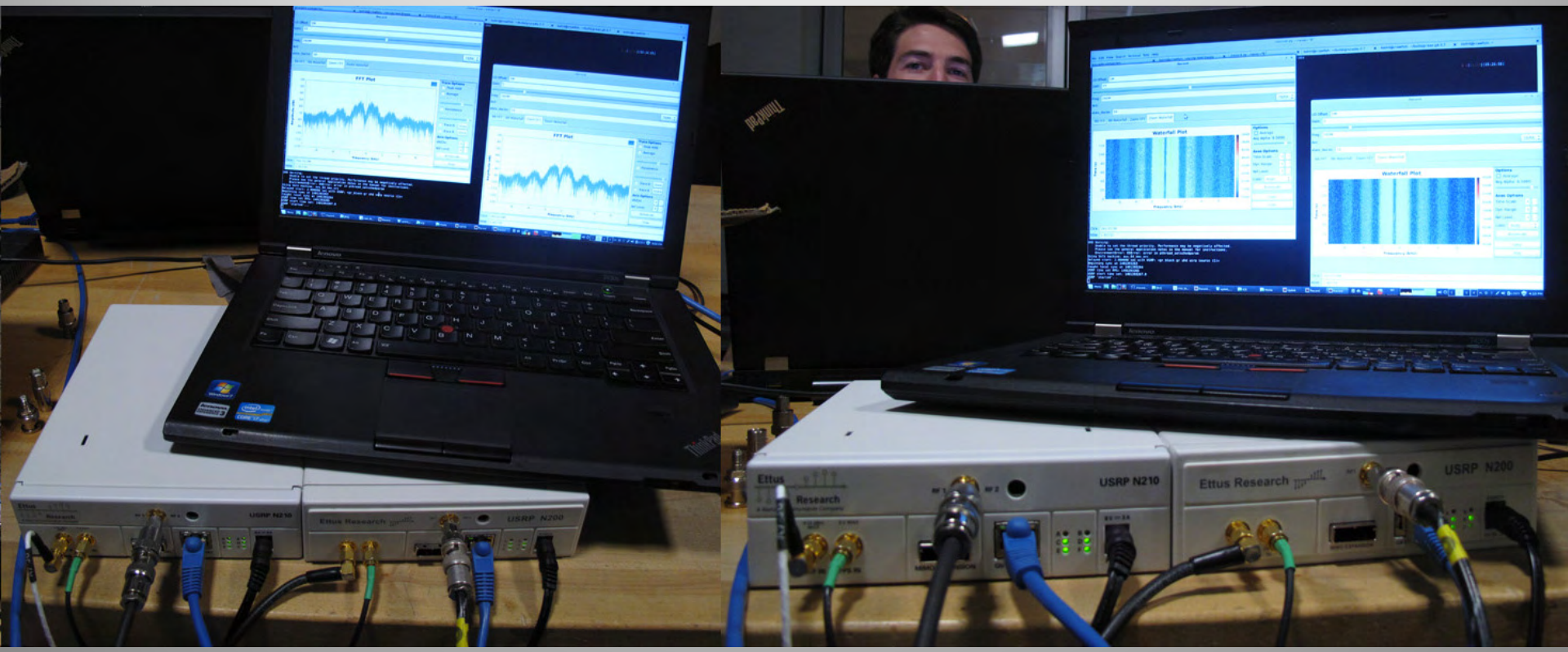
Commanding

- Transponder B did not respond to commands
  - Perhaps we had a marginal link to the space probe based on antenna, receiver and distance
- Transponder A *did* respond
  - TLM was successfully re-enabled
- Then commanded TLM to be enabled on B, uplinked via A

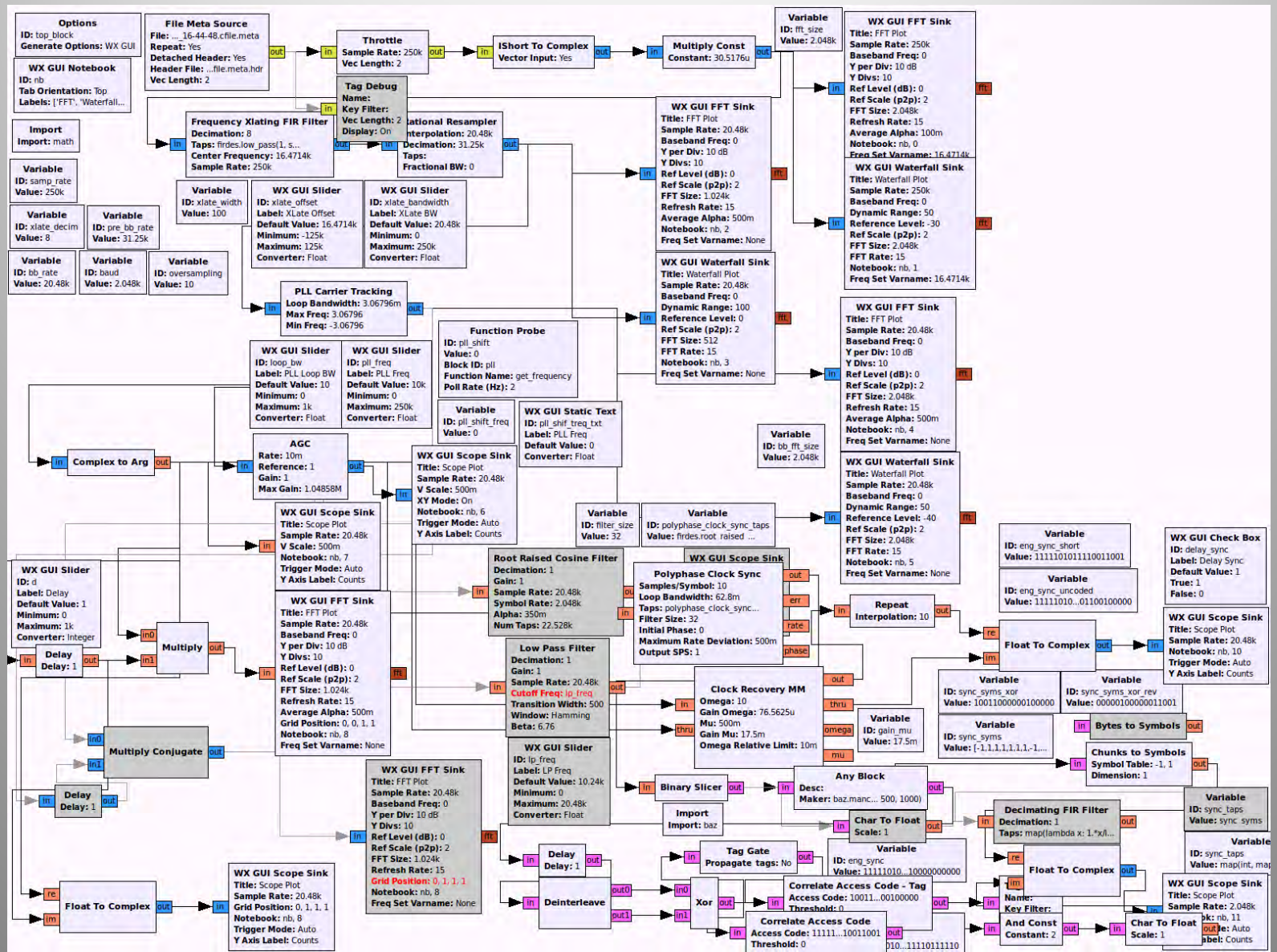
TLM on A and B


./record.py --name="B"
File Edit View Search Terminal Tabs Help
gnuradio-companion
balint@crawfish: ~/src/gr-isee3/apps
./record.py --name="B"
balint@crawfish: ~/build/gnuradio-3.7
balint@crawfish: ~/build/gr-baz.git-3.7
balint@crawfish: ~
Record
LO Offset: 1M
Gain: 15
Freq: 260M
Ant: TX/RX
xlate_decim: 16
BB FFT
BB Waterfall
Zoom FFT
Zoom Waterfall
FFT Plot
Amplitude (dB)
Frequency (kHz)
Trace Options
Peak Hold
Average
Avg Alpha: 0.1333
Persistence
Persist Alpha: 0.8074
Trace A
Trace B
Store
Axis Options
dB/Div:
Ref Level:
Autoscale
Stop
Click: 260.017M
RBW: 1.90735
UHD Warning:
Unable to set the thread priority. Performance may be negatively affected.
Please see the general application notes in the manual for instructions.
EnvironmentError: OSError: error in pthread_setschedparam
Using Volk machine: avx_64_mmx_orc
Delayed start: 2.000000 sec with USRP: <gr_block gr uhd usrp source (1)>
Beginning sync at 1401393263
Caught local sync at 1401393264
USRP time set PPS: 1401393265
USRP start time set: 1401393267.0
USRP 'started'...
make
1 ↵[11133][15:26:55]
Record
LO Offset: 1M
Gain: 5
Freq: 260M
Ant: TX/RX
xlate_decim: 16
BB FFT
BB Waterfall
Zoom FFT
Zoom Waterfall
FFT Plot
Amplitude (dB)
Frequency (kHz)
Trace Options
Peak Hold
Average
Avg Alpha: 0.1333
Persistence
Persist Alpha: 0.8074
Trace A
Trace B
Store
Axis Options
dB/Div:
Ref Level:
Autoscale
Stop
Click: 260.019M
RBW: 1.90735
Menu
./record...
[RX]
cmd_lis...
Record....
uplink_...
ICE
Home
Uplink
Record
Record
4:07 PM

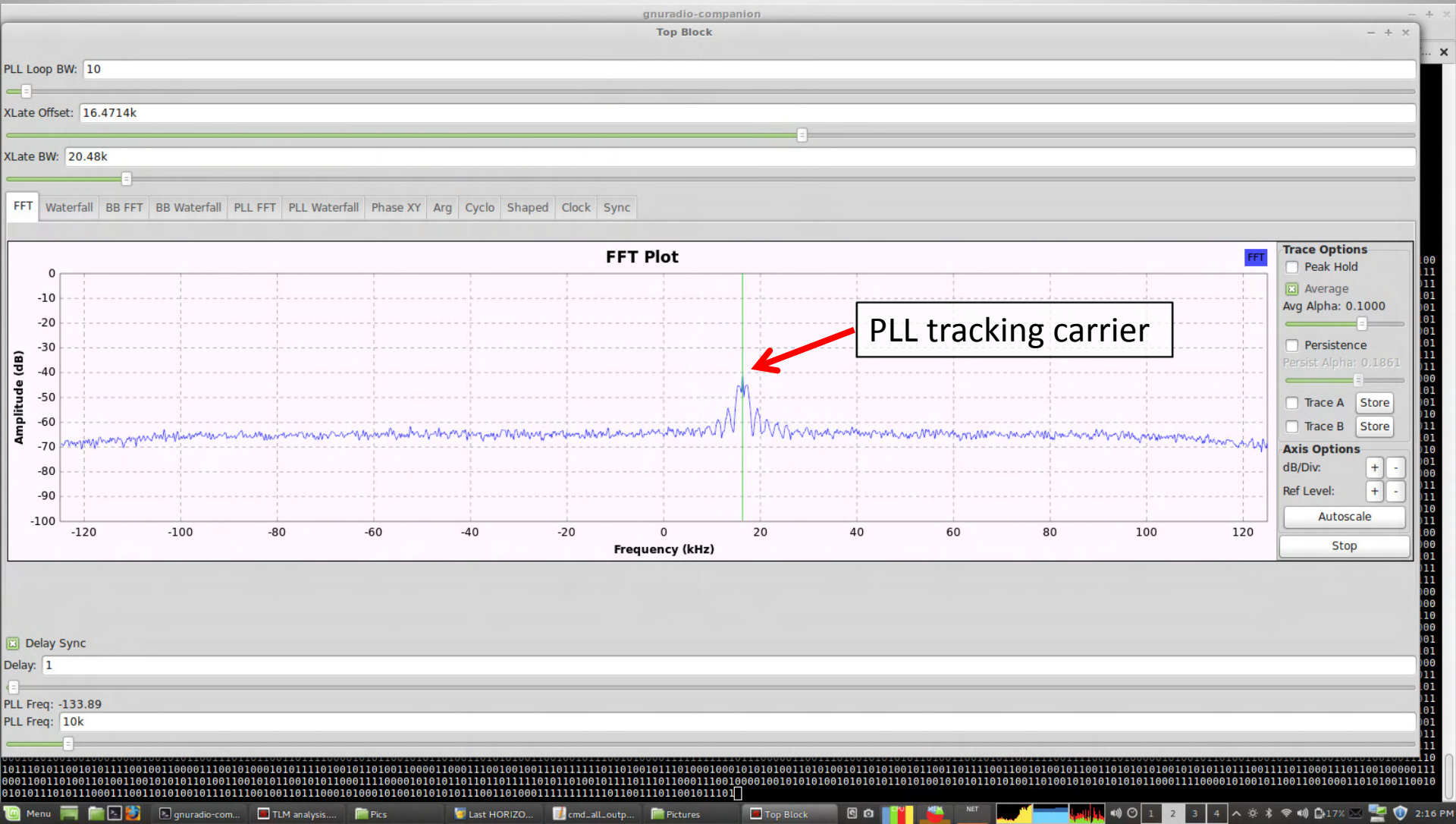
Recording Telemetry



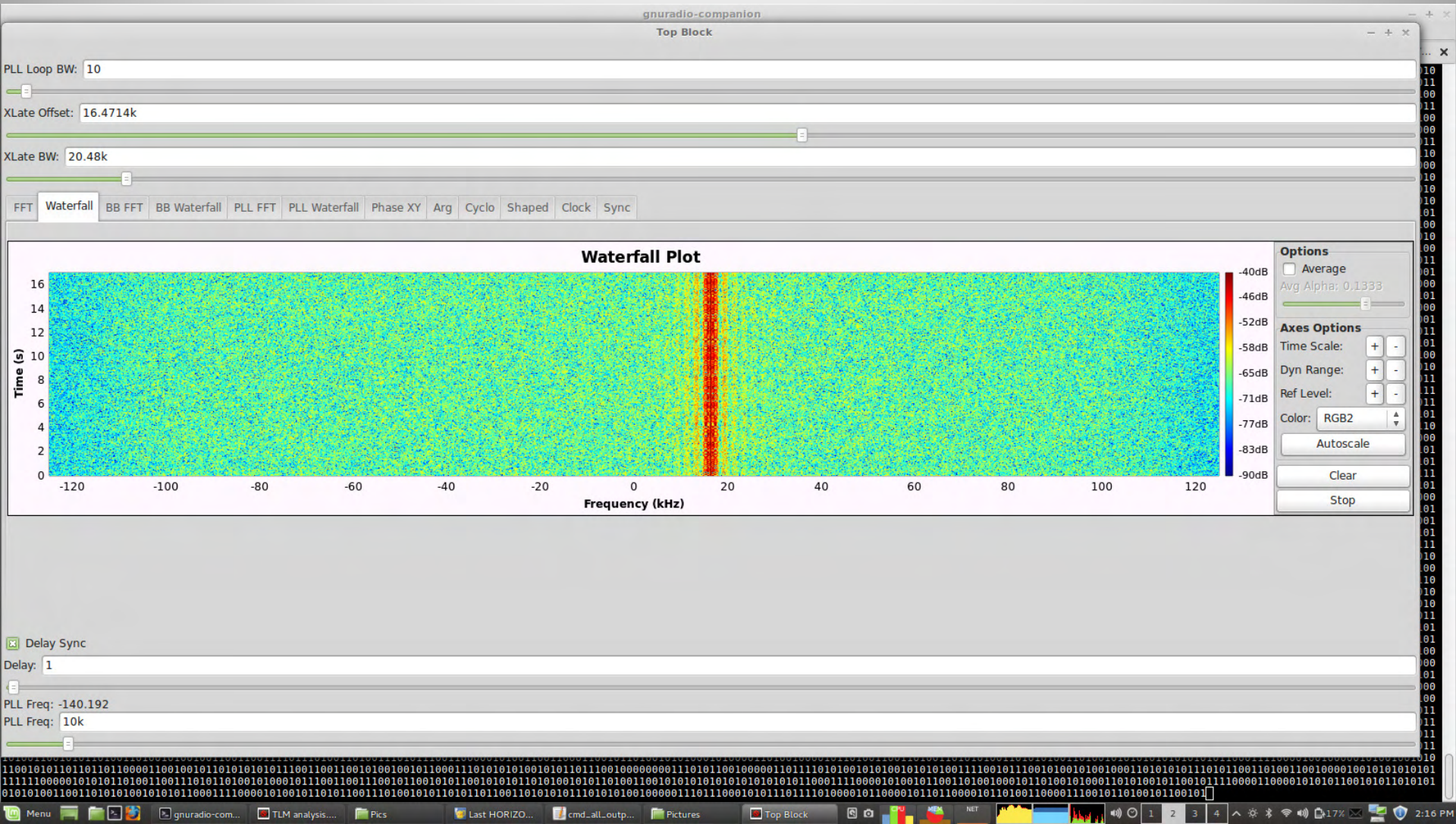
Analysing Telemetry



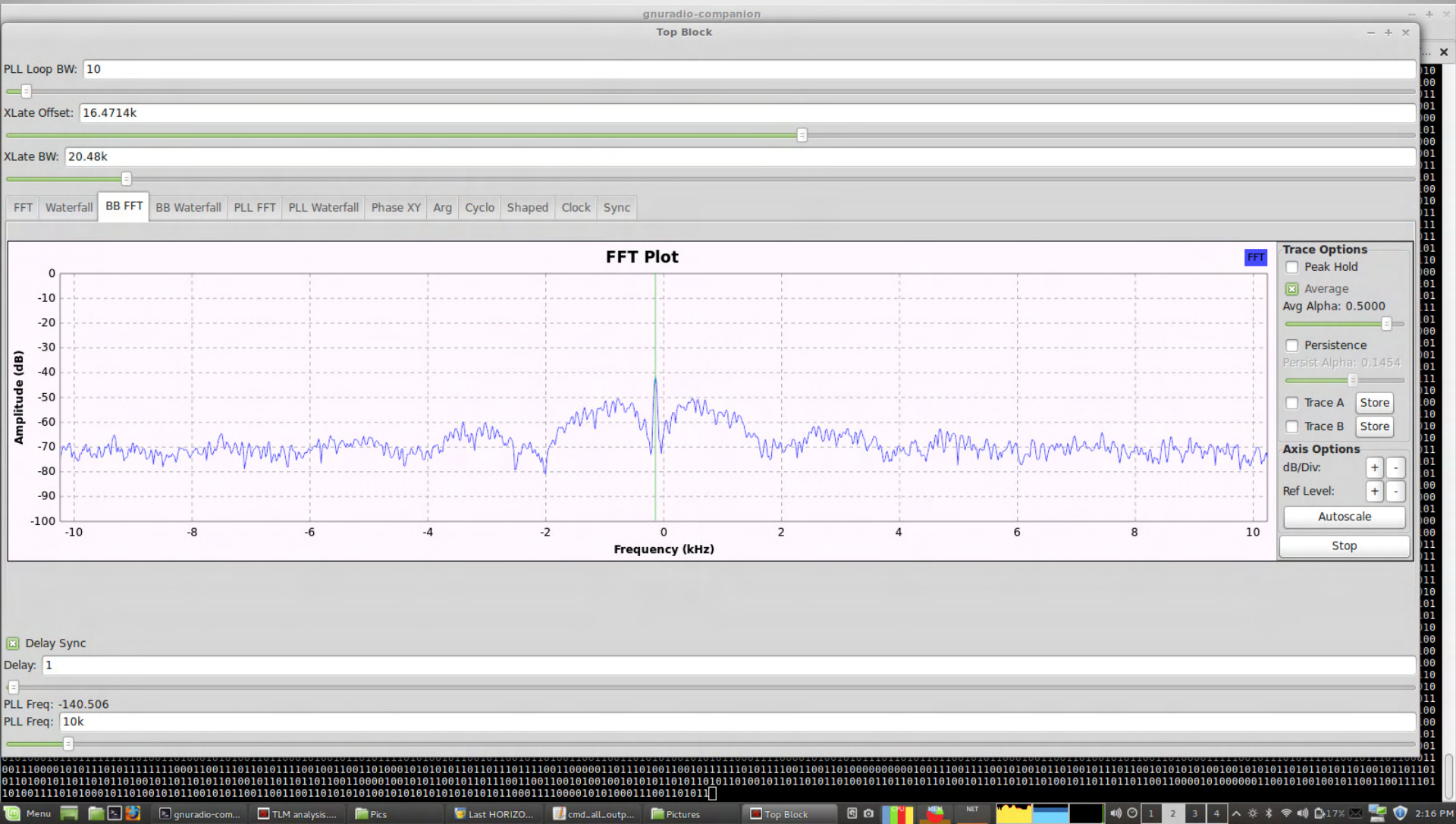
Raw Captured Baseband



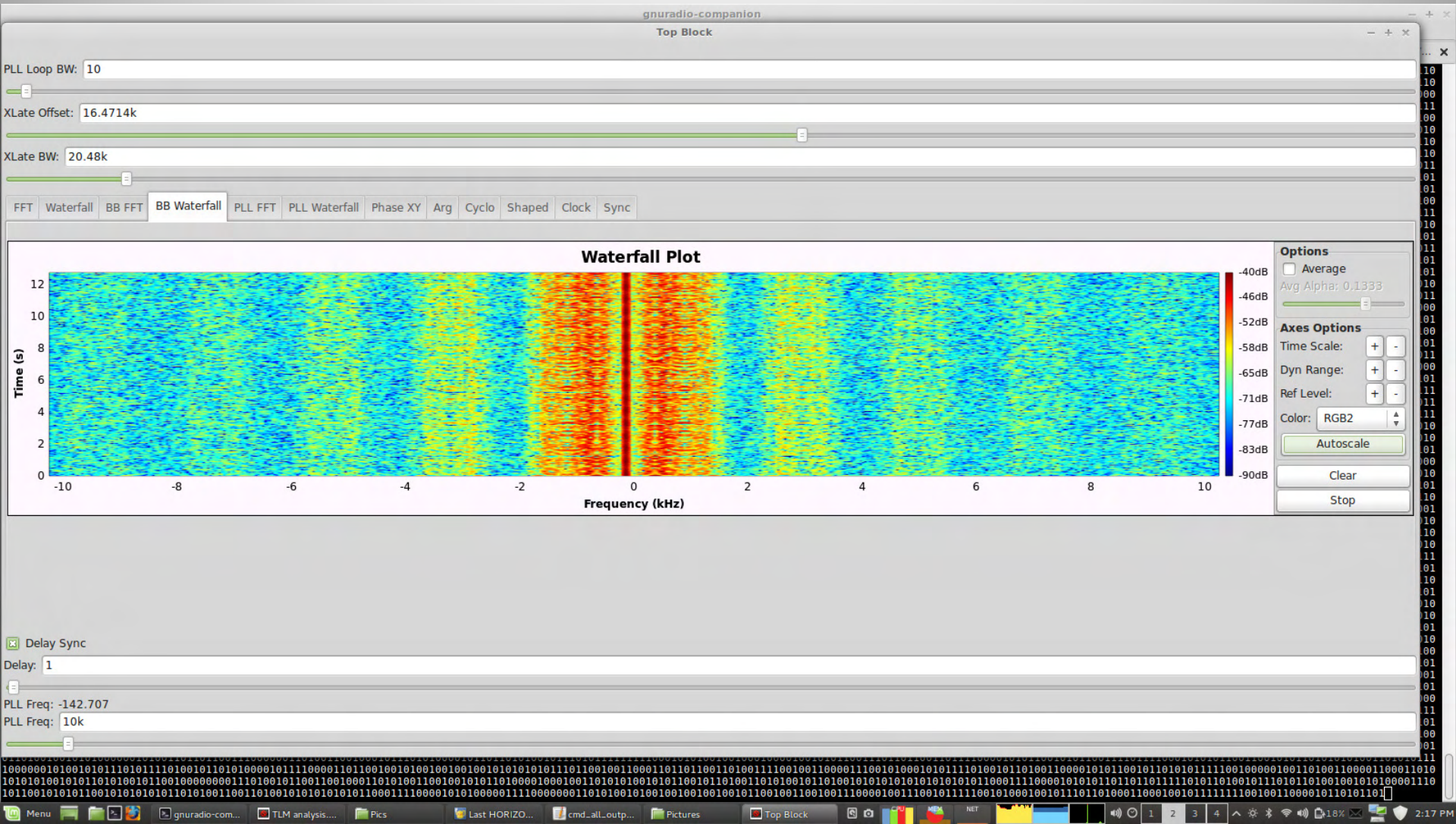
Raw Captured Baseband



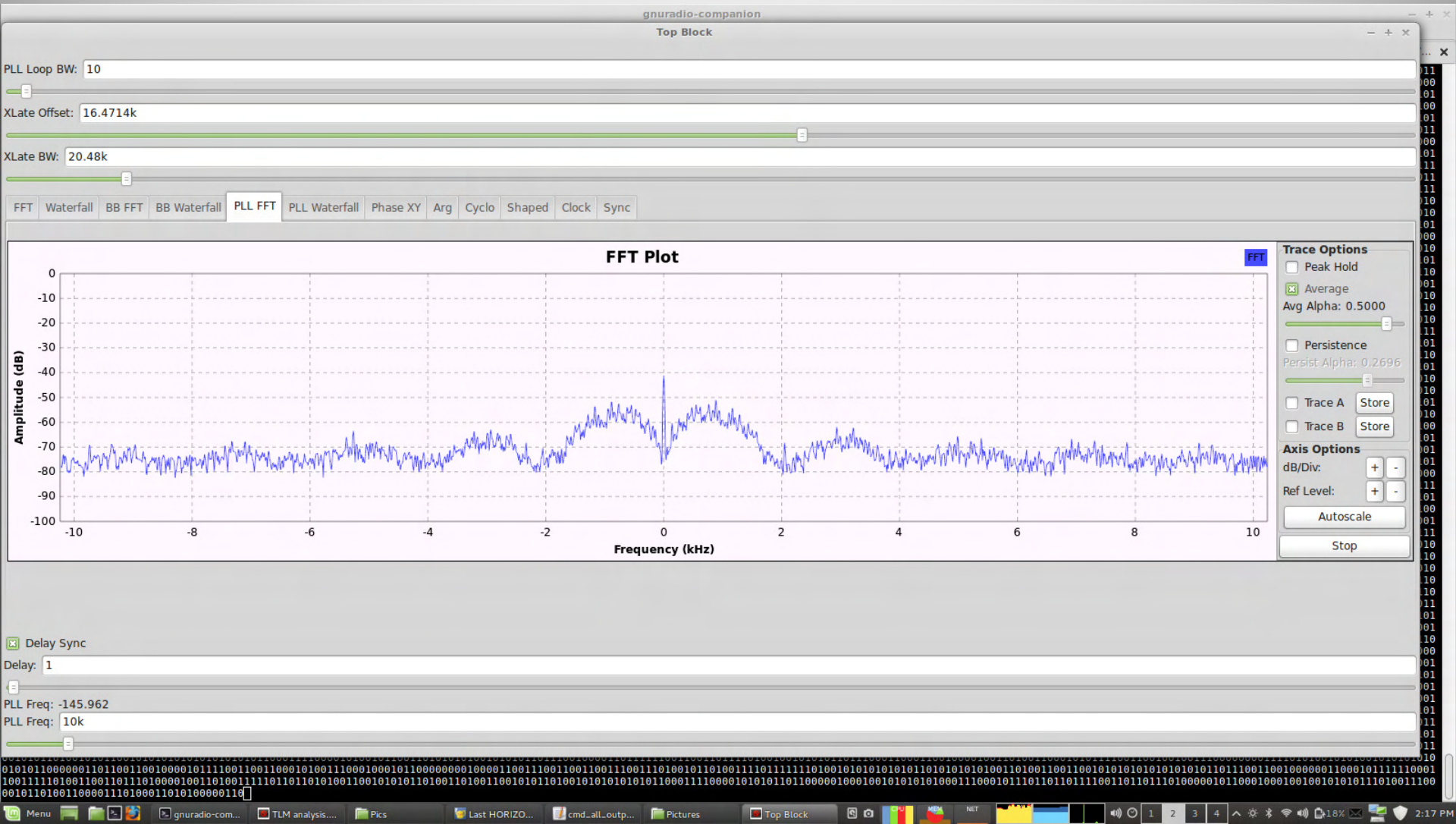
Zoomed Baseband



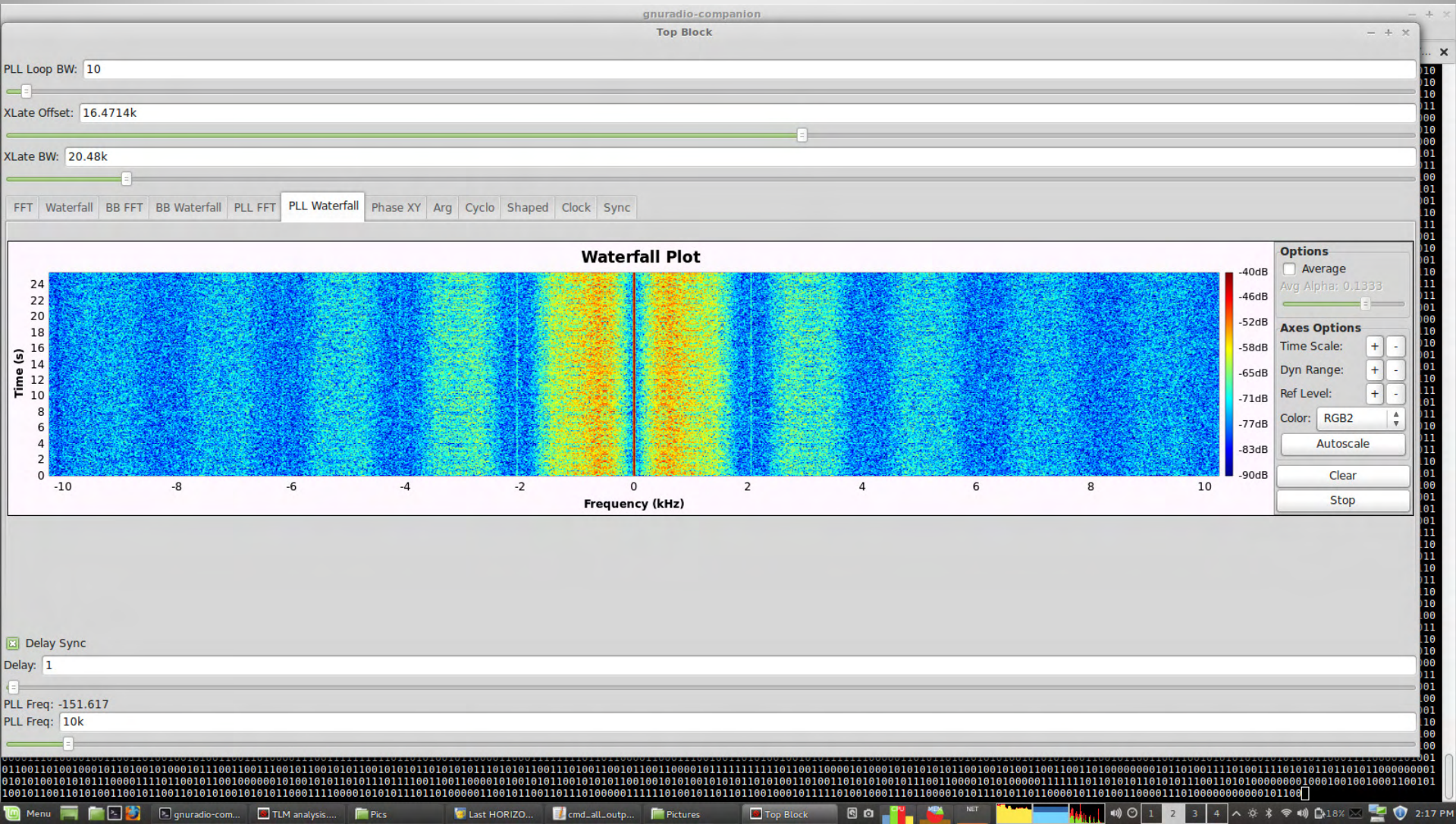
Zoomed Baseband



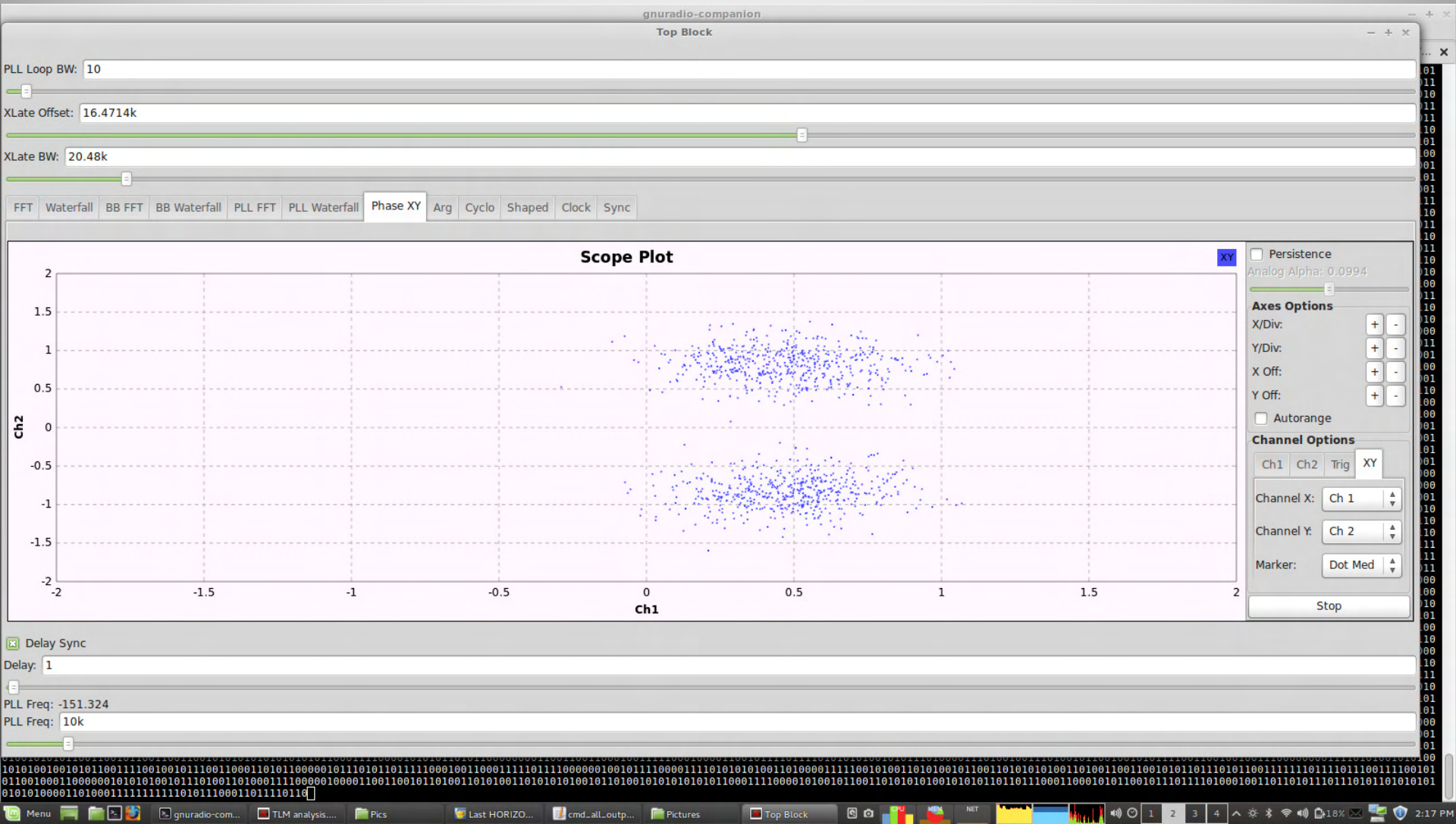
PLL Lock


gnuradio-companion
Top Block
PLL Loop BW: 10
XLate Offset: 16.4714k
XLate BW: 20.48k
FFT
Waterfall
BB FFT
BB Waterfall
PLL FFT
PLL Waterfall
Phase XY
Arg
Cyclo
Shaped
Clock
Sync
FFT Plot
FFT
Amplitude (dB)
Frequency (kHz)
Trace Options
Peak Hold
Average
Avg Alpha: 0.5000
Persistence
Persist Alpha: 0.2696
Trace A
Store
Trace B
Store
Axis Options
dB/Div:
Ref Level:
Autoscale
Stop
Delay Sync
Delay: 1
PLL Freq: -145.962
PLL Freq: 10k

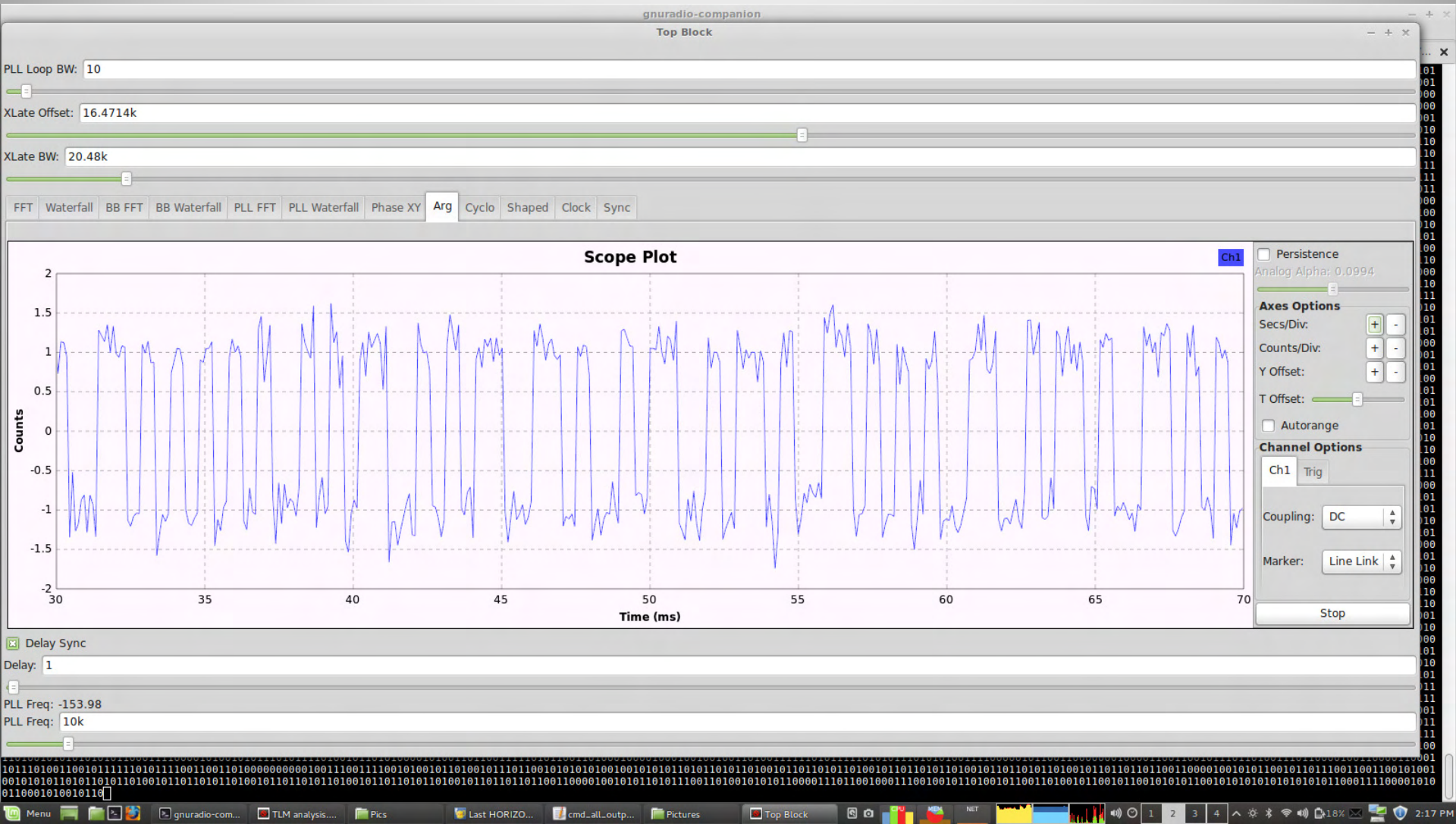
PLL Lock


gnuradio-companion
Top Block
PLL Loop BW: 10
XLate Offset: 16.4714k
XLate BW: 20.48k
FFT
Waterfall
BB FFT
BB Waterfall
PLL FFT
PLL Waterfall
Phase XY
Arg
Cyclo
Shaped
Clock
Sync
Waterfall Plot
Time (s)
Frequency (kHz)
-40dB
-46dB
-52dB
-58dB
-65dB
-71dB
-77dB
-83dB
-90dB
Options
Average
Avg Alpha: 0.1333
Axes Options
Time Scale:
Dyn Range:
Ref Level:
Color: RGB2
Autoscale
Clear
Stop
Delay Sync
Delay: 1
PLL Freq: -151.617
PLL Freq: 10k

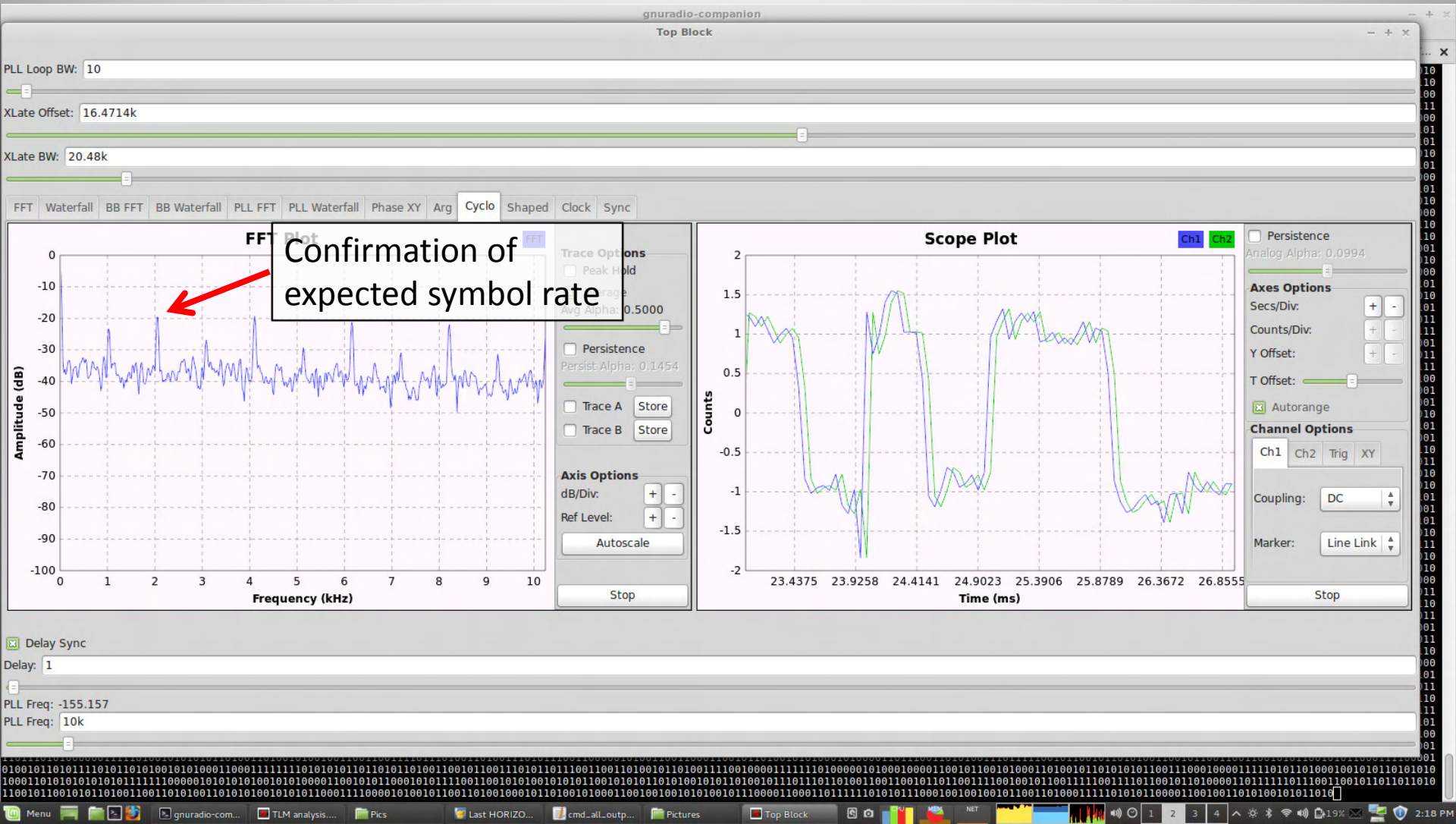
IQ Scope Plot



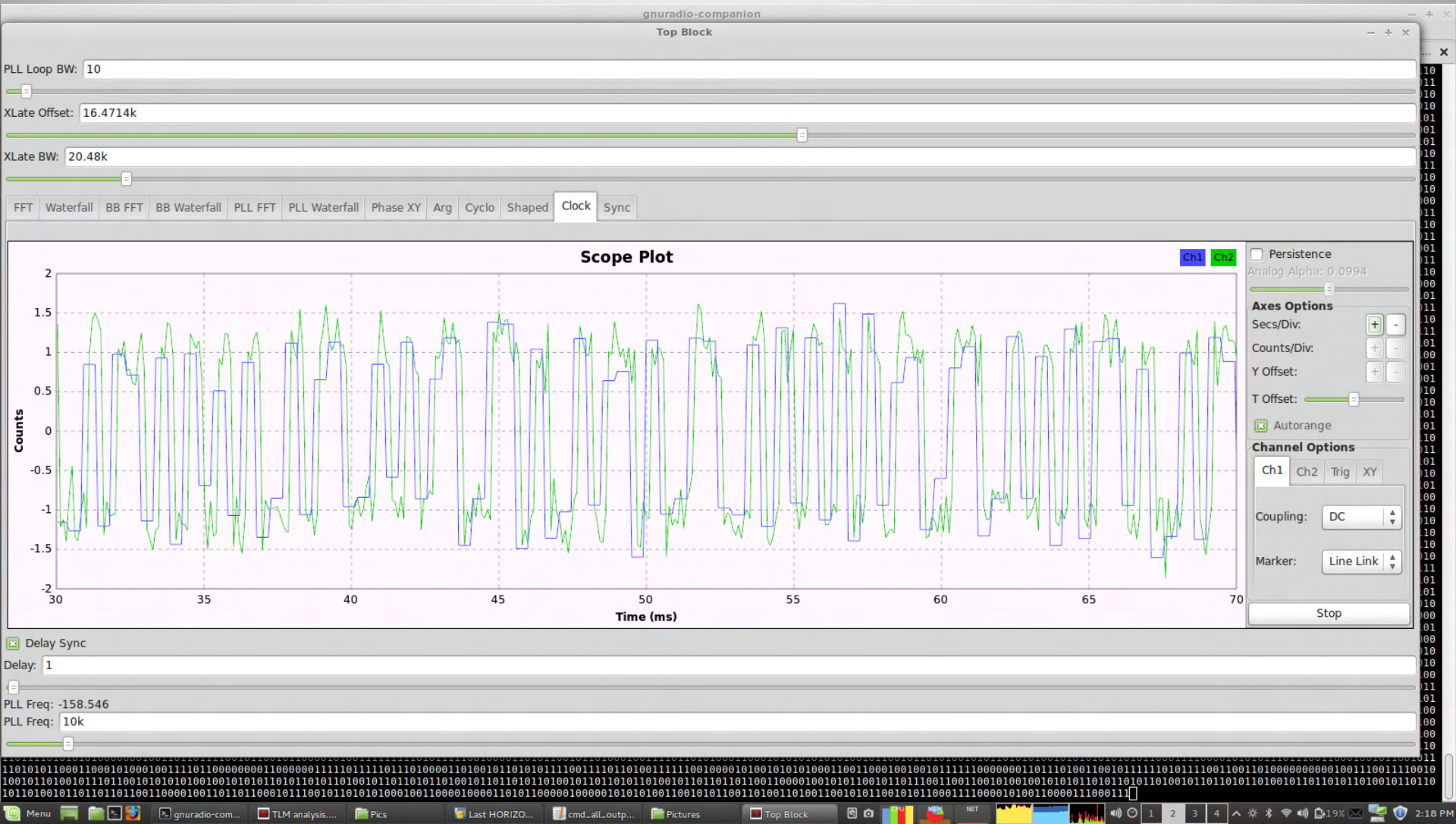
Raw Phase Demodulation



Cyclostationary Analysis

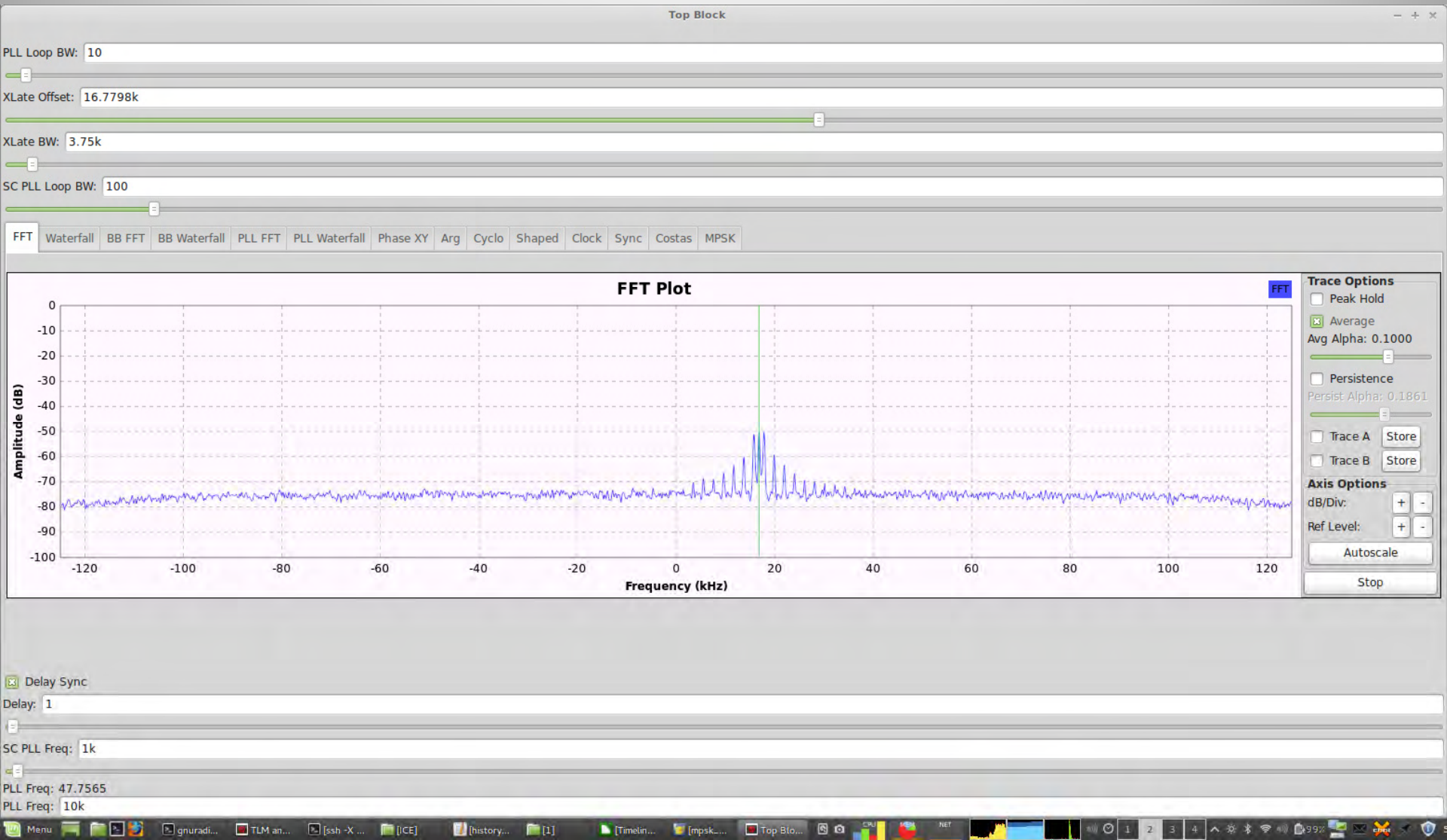


Clock Recovery & Sampling



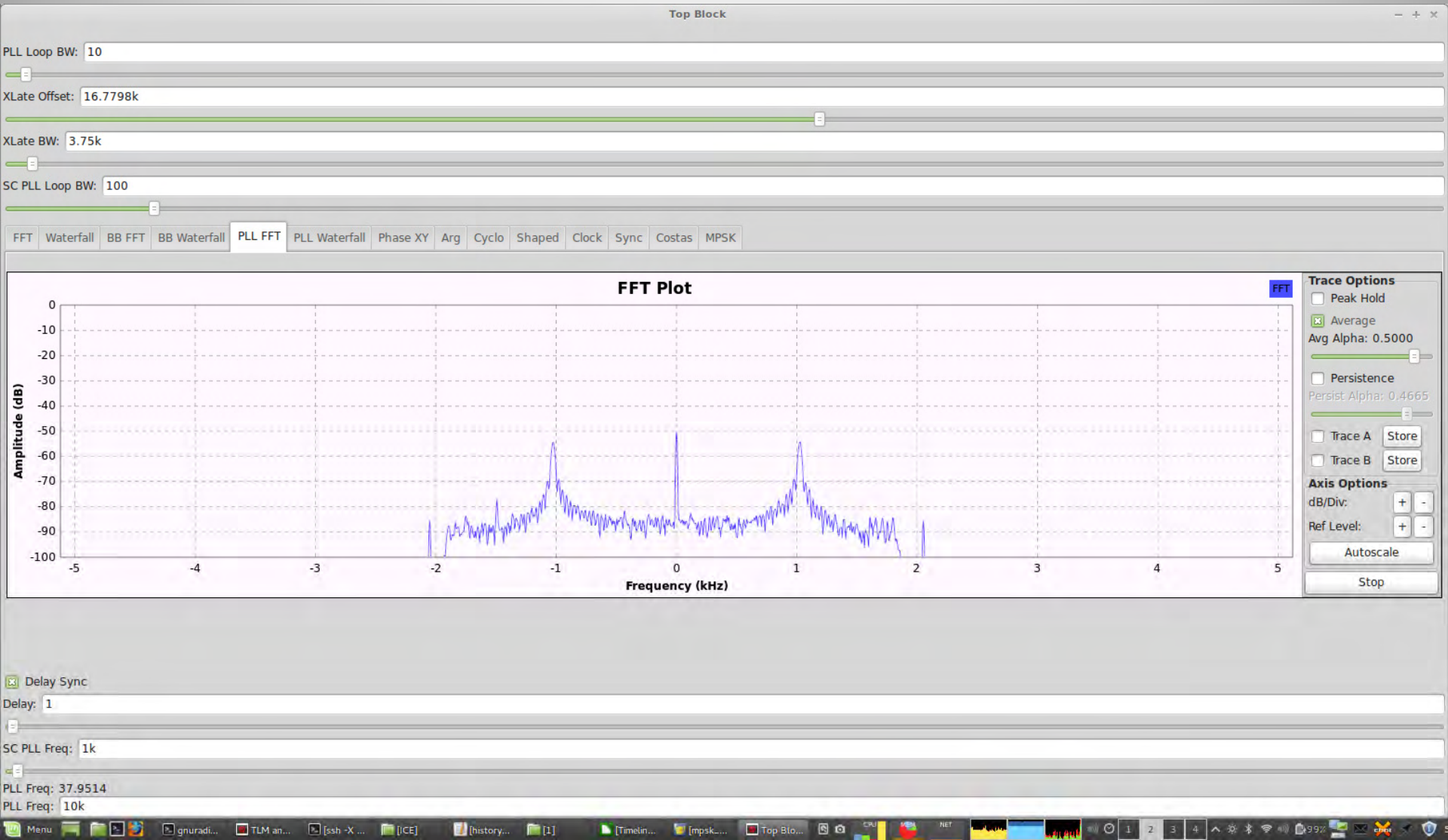
Sync Correlation Peak

Low-rate w/ 1024 Hz sub-carrier

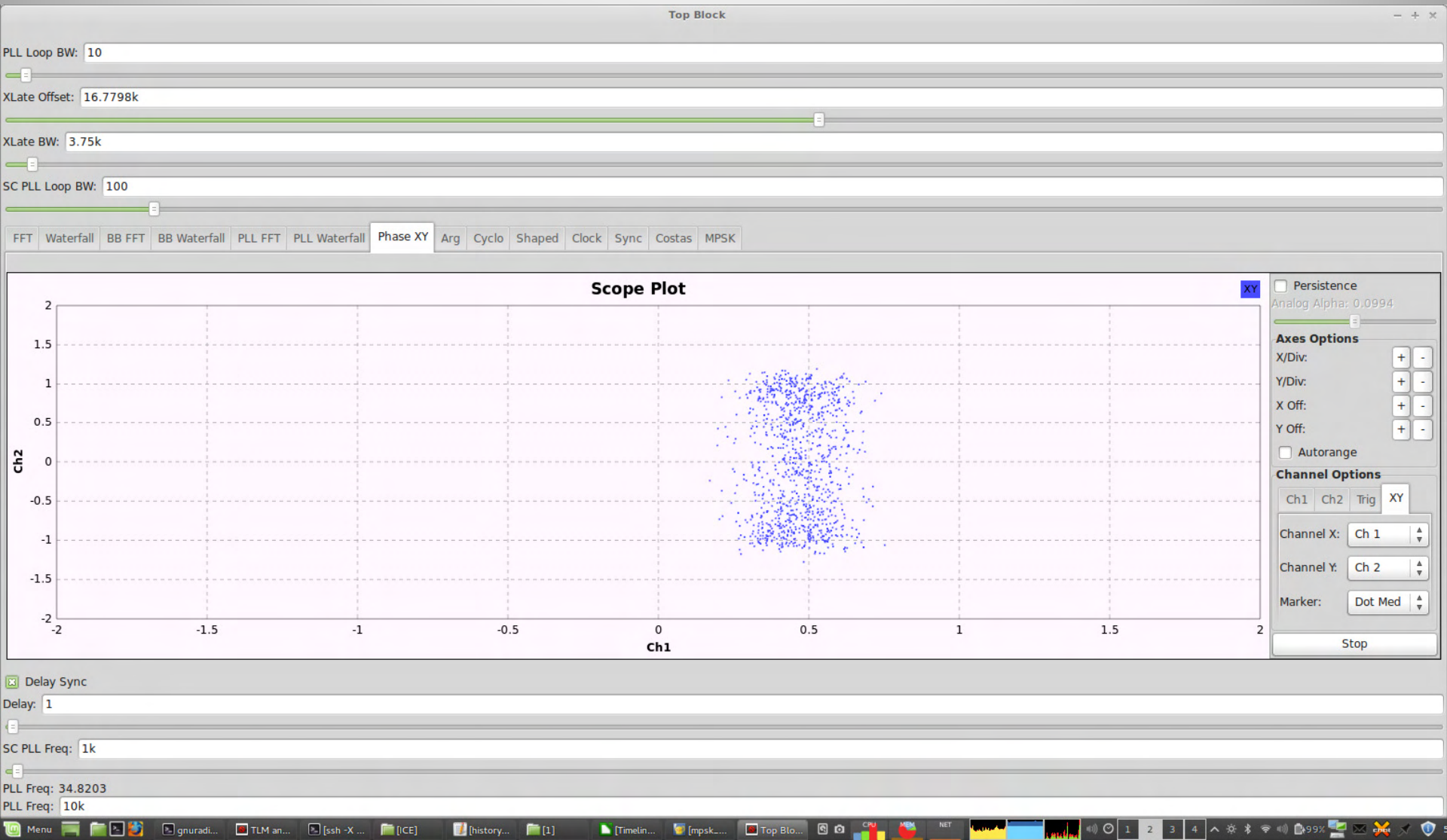


Zoomed Baseband

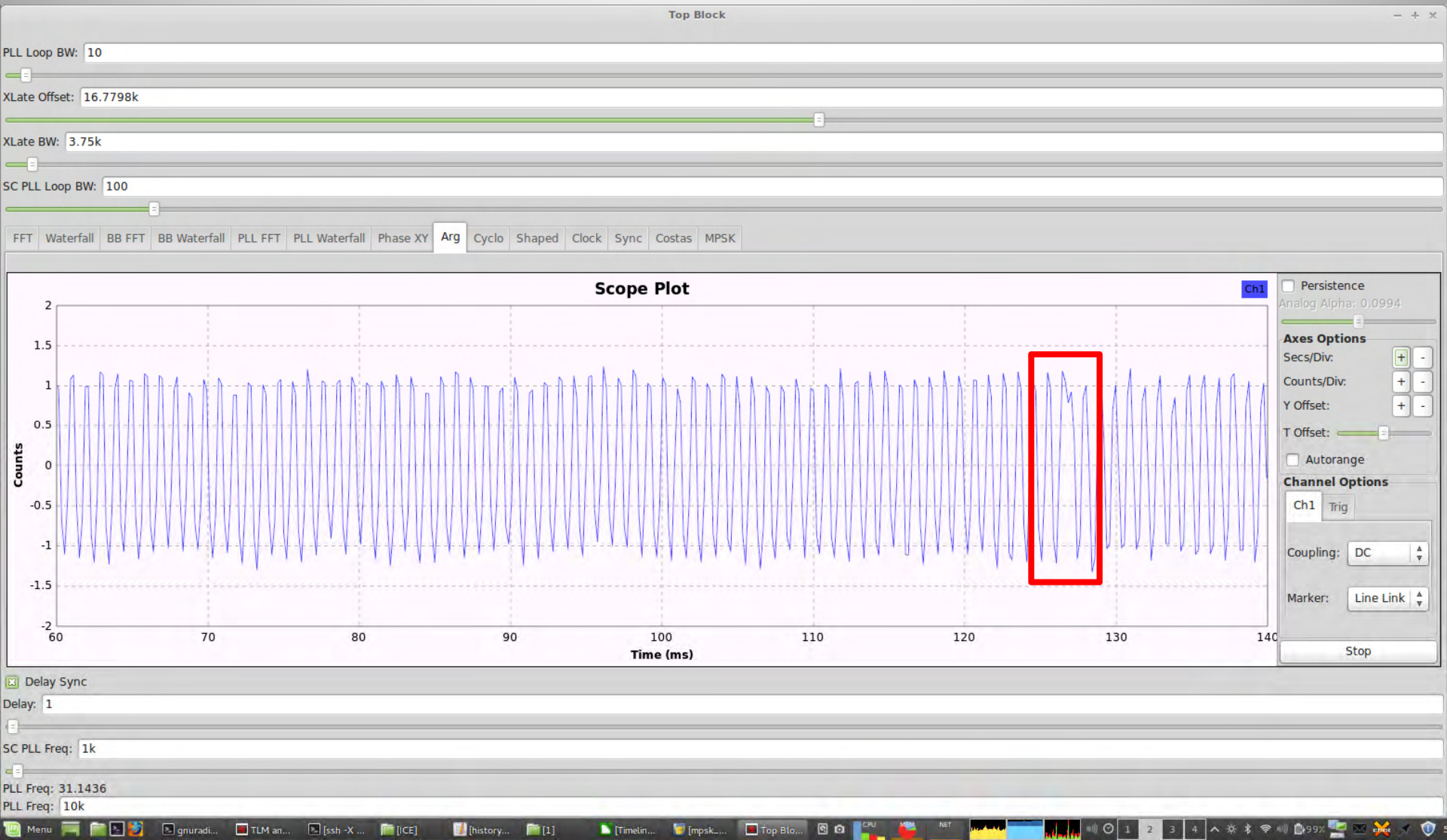
PLL Lock


Top Block
PLL Loop BW: 10
XLate Offset: 16.7798k
XLate BW: 3.75k
SC PLL Loop BW: 100
FFT
Waterfall
BB FFT
BB Waterfall
PLL FFT
PLL Waterfall
Phase XY
Arg
Cyclo
Shaped
Clock
Sync
Costas
MPSK
FFT Plot
FFT
Amplitude (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-5
-4
-3
-2
-1
0
1
2
3
4
5
Frequency (kHz)
Trace Options
Peak Hold
Average
Avg Alpha: 0.5000
Persistence
Persist Alpha: 0.4665
Trace A
Store
Trace B
Store
Axis Options
dB/Div:
Ref Level:
Autoscale
Stop
Delay Sync
Delay: 1
SC PLL Freq: 1k
PLL Freq: 37.9514
PLL Freq: 10k

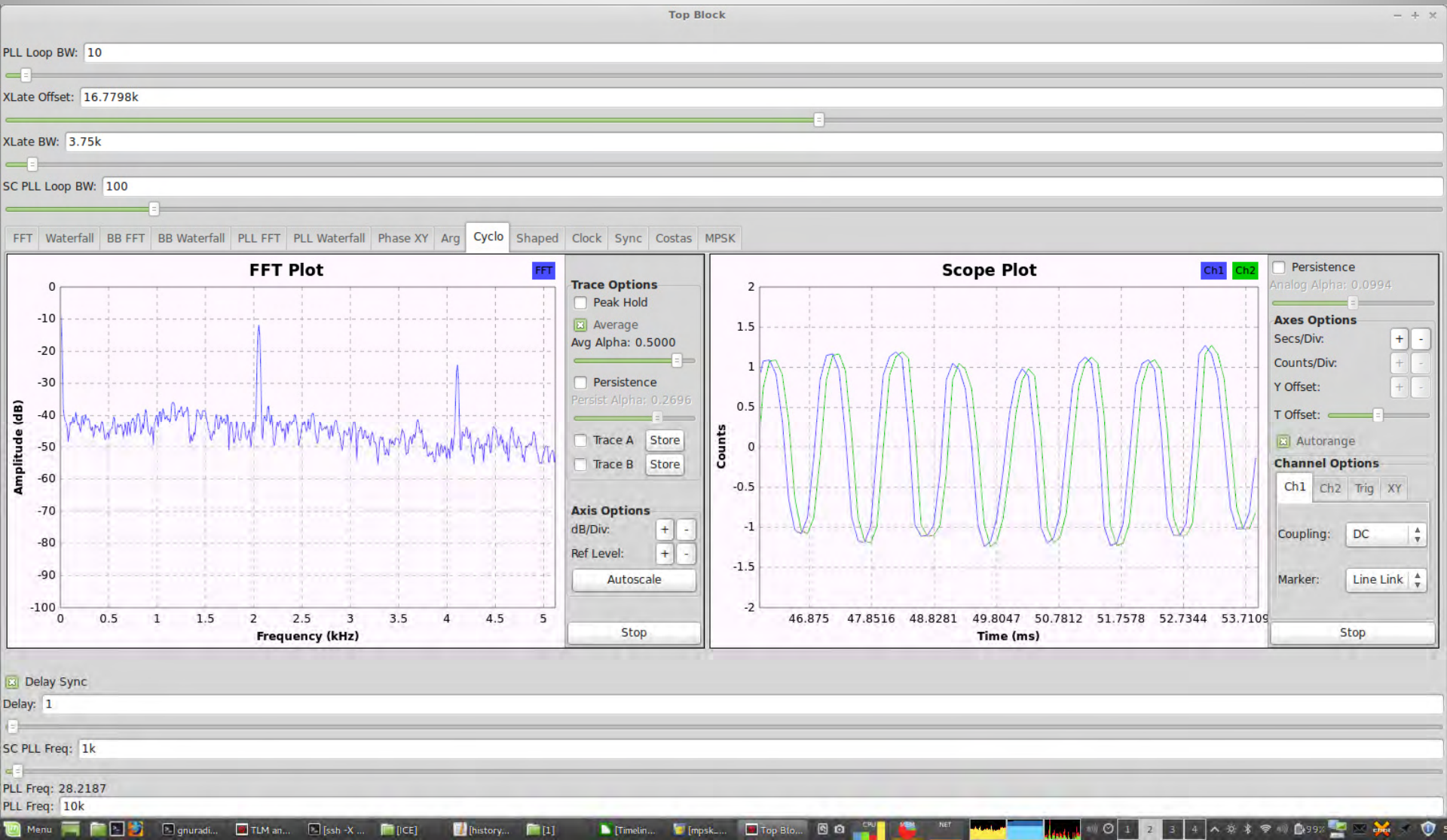
IQ Scope Plot



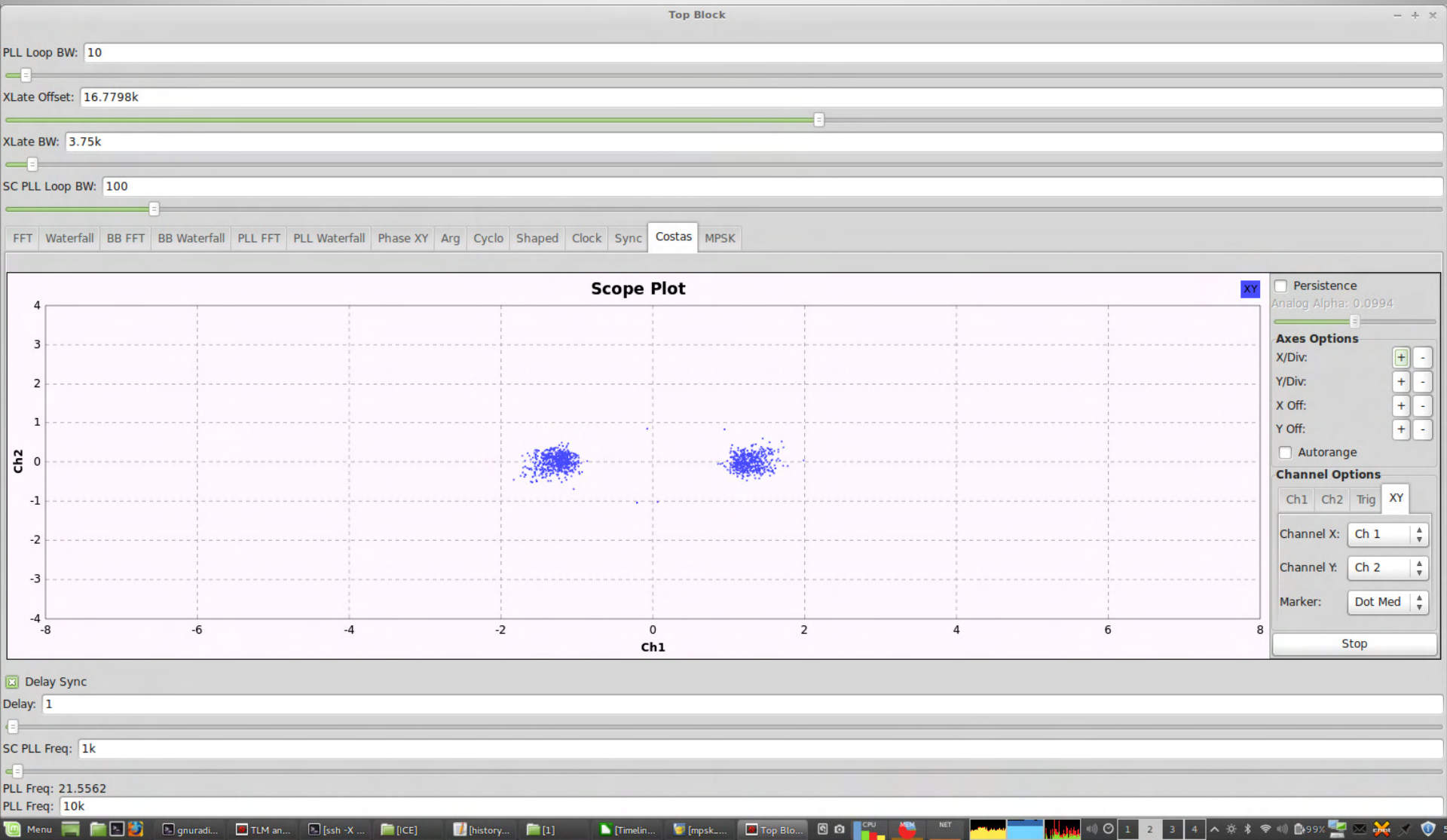
1024 Hz Sub-carrier



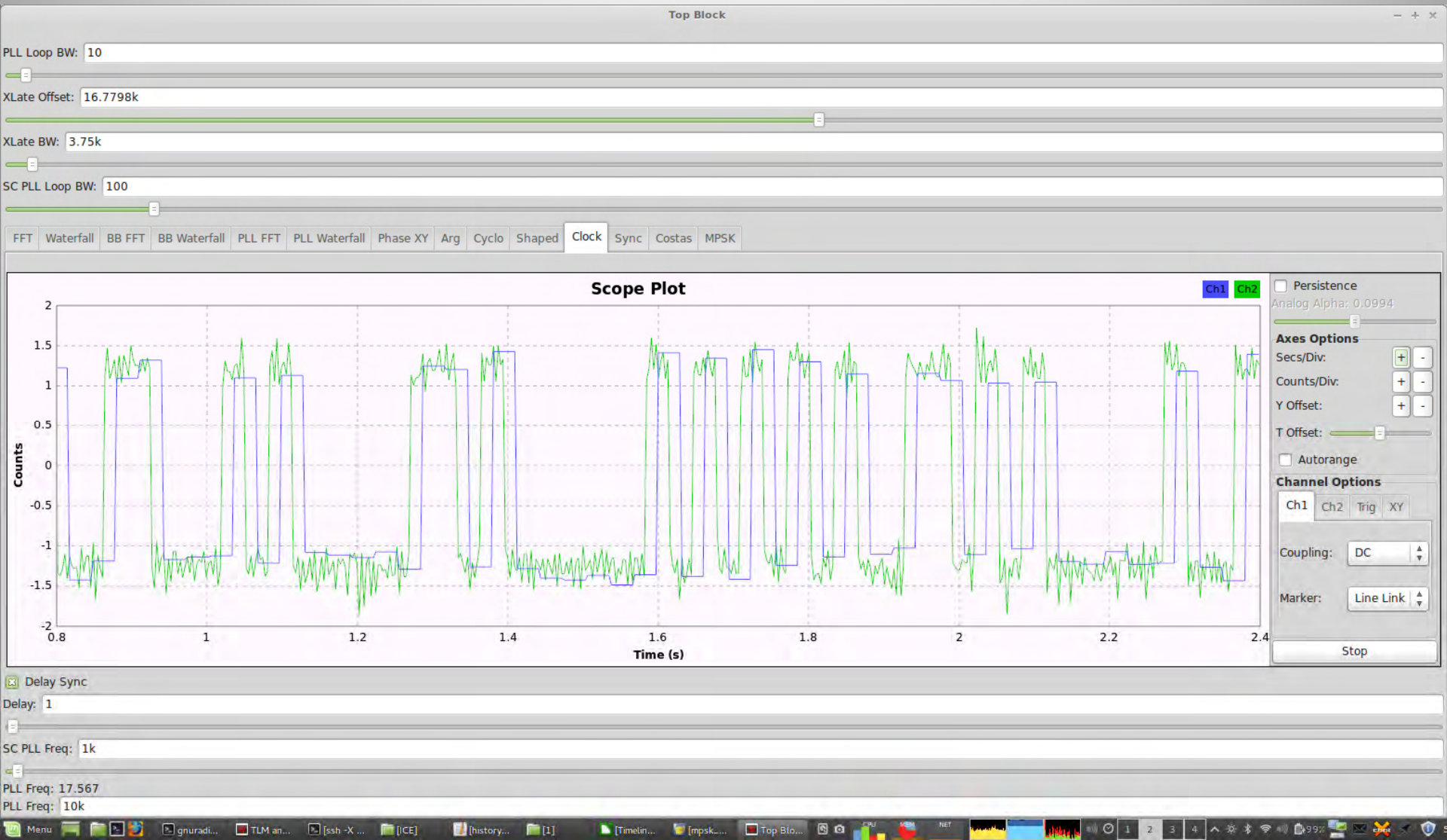
Cyclostationary Analysis



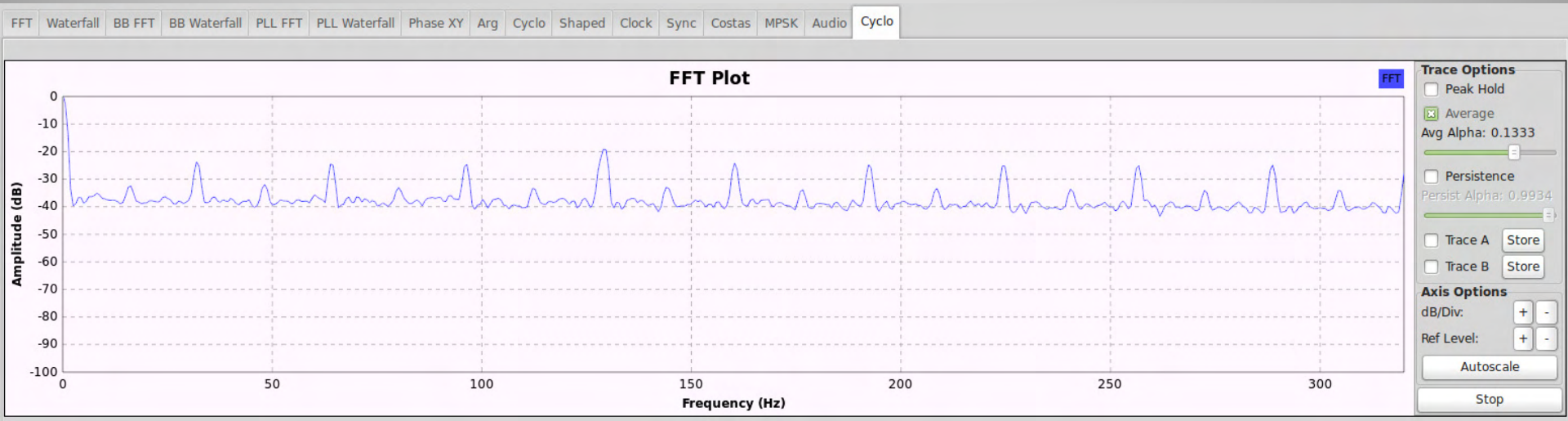
Costas


Top Block
PLL Loop BW: 10
XLate Offset: 16.7798k
XLate BW: 3.75k
SC PLL Loop BW: 100
FFT
Waterfall
BB FFT
BB Waterfall
PLL FFT
PLL Waterfall
Phase XY
Arg
Cyclo
Shaped
Clock
Sync
Costas
MPSK
Scope Plot
XY
Ch2
Ch1
Persistence
Analog Alpha: 0.0994
Axes Options
X/Div:
Y/Div:
X Off:
Y Off:
Autorange
Channel Options
Ch1
Ch2
Trig
XY
Channel X: Ch 1
Channel Y: Ch 2
Marker: Dot Med
Stop
Delay Sync
Delay: 1
SC PLL Freq: 1k
PLL Freq: 21.5562
PLL Freq: 10k

Clock Recovery & Sampling



Sub-carrier Cyclostationary Analysis



Telemetry

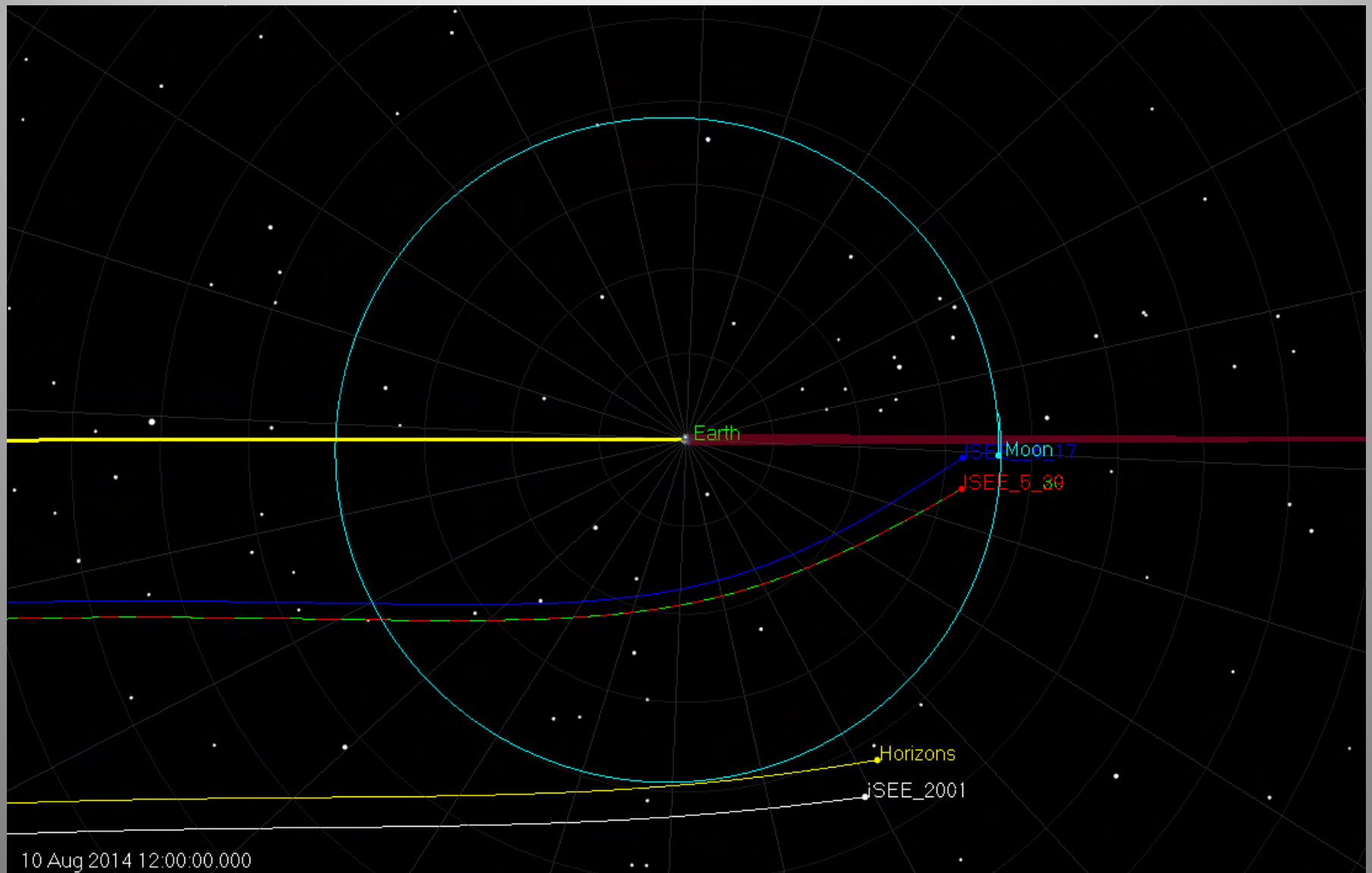
- The legendary Phil Karn (@ka9q) has contributed his considerable expertise & prototype convolutional decoder

- Will attempt to GNU Radio-erise…

Portion of Received Telemetry

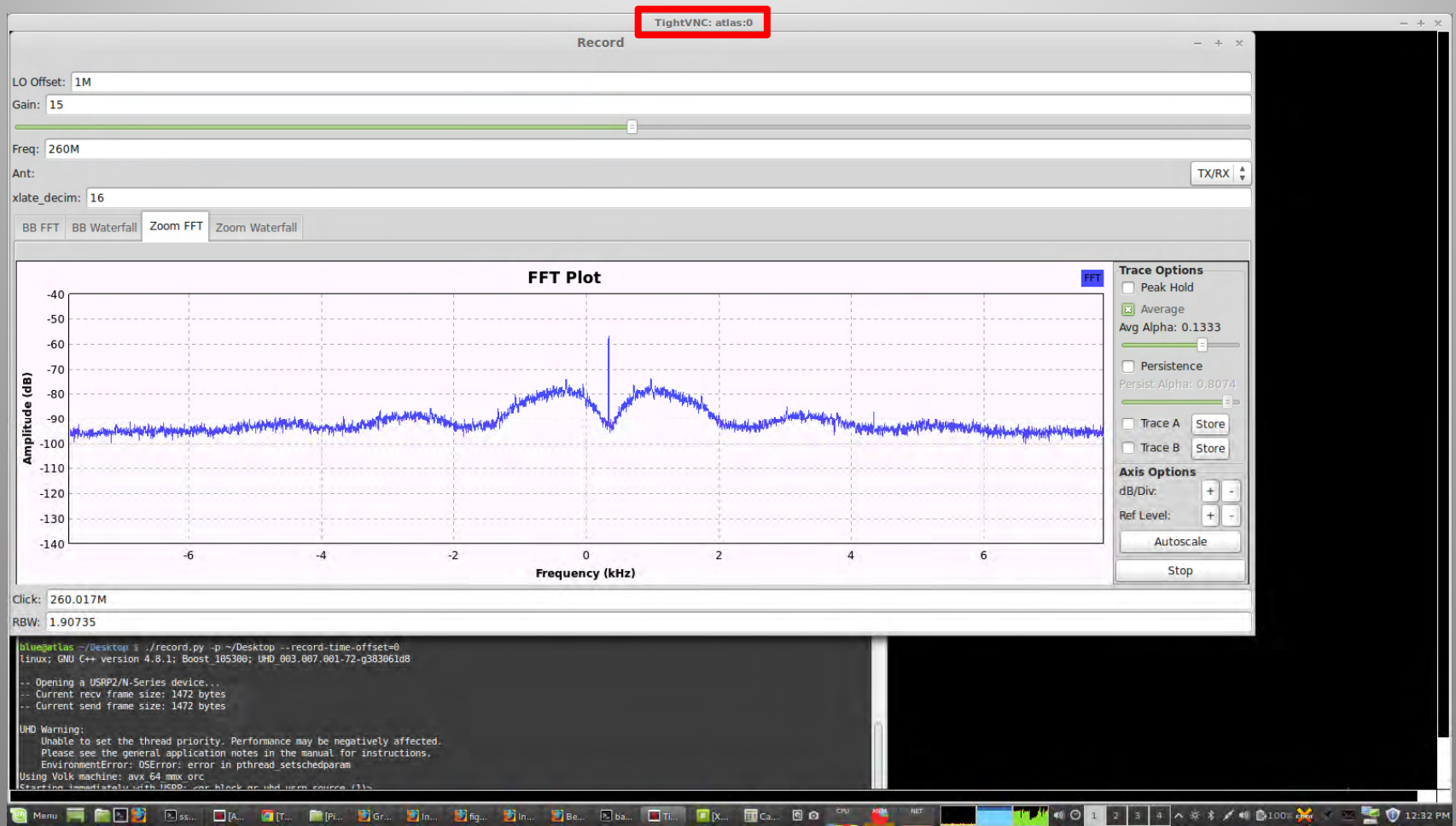
- ISEE-3 Power System Status
  - Main bus voltage >= 28 volts
  - Solar array current >= 5.2 amps
  - Essential bus current <= 0.25 amps
  - Non-essential bus current = 4 amps
  - Shunt dump current >= 1 amp
  - Transponder A RF power = 5 watts
  - Transponder B RF power = 5.25 watts

Improved Ephemeris

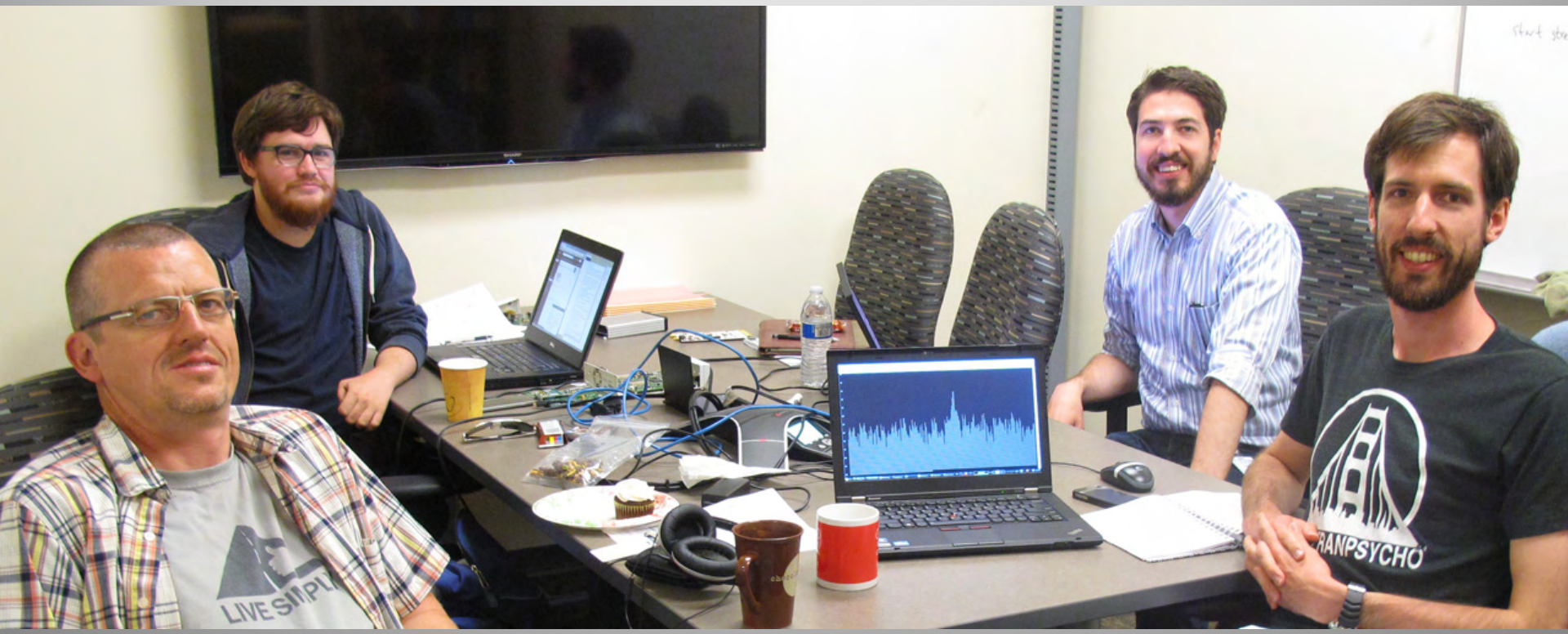


Remote Operations

- RX & TX USRPs now hosted at Arecibo



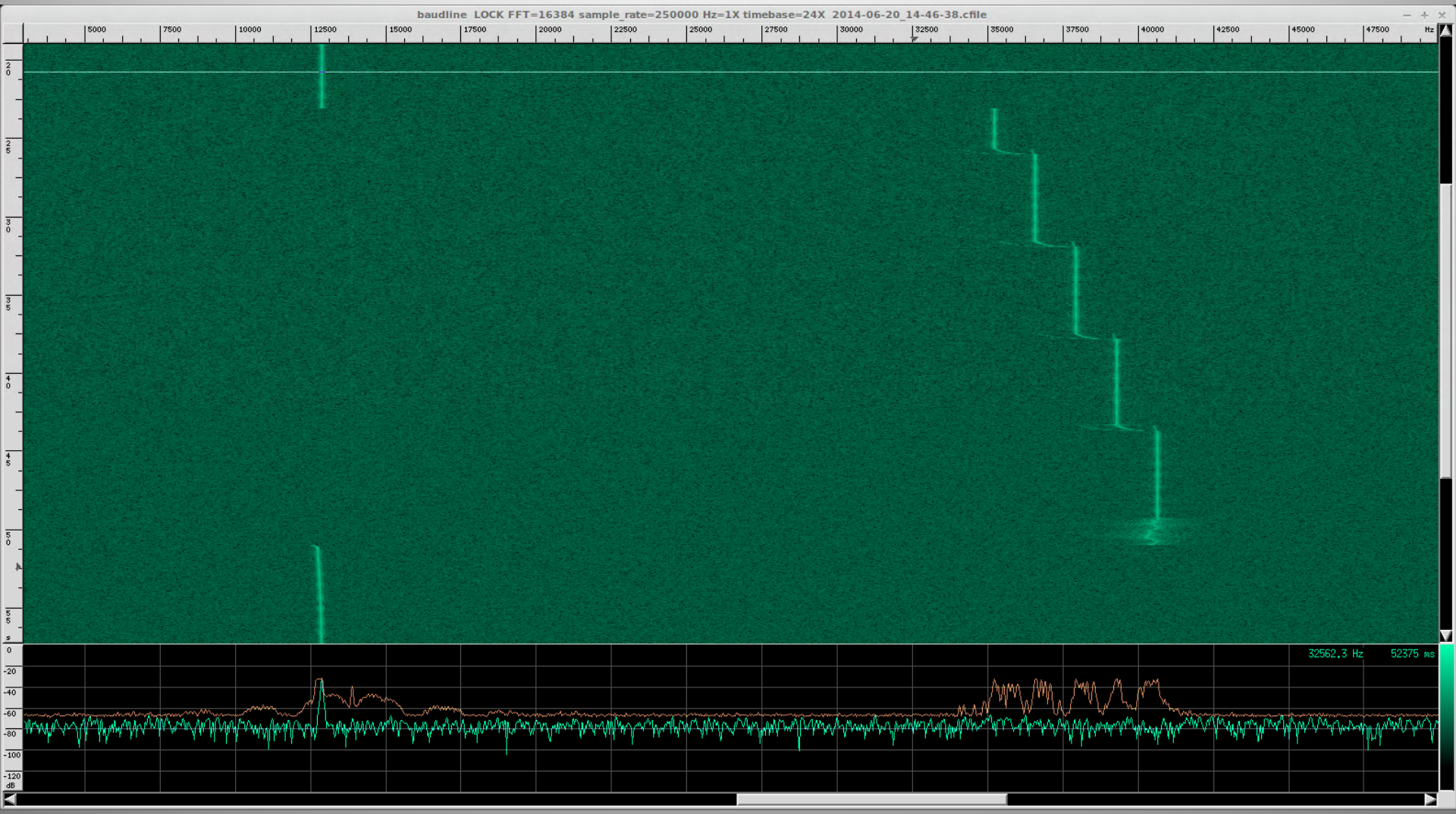
ASCII-art FFT



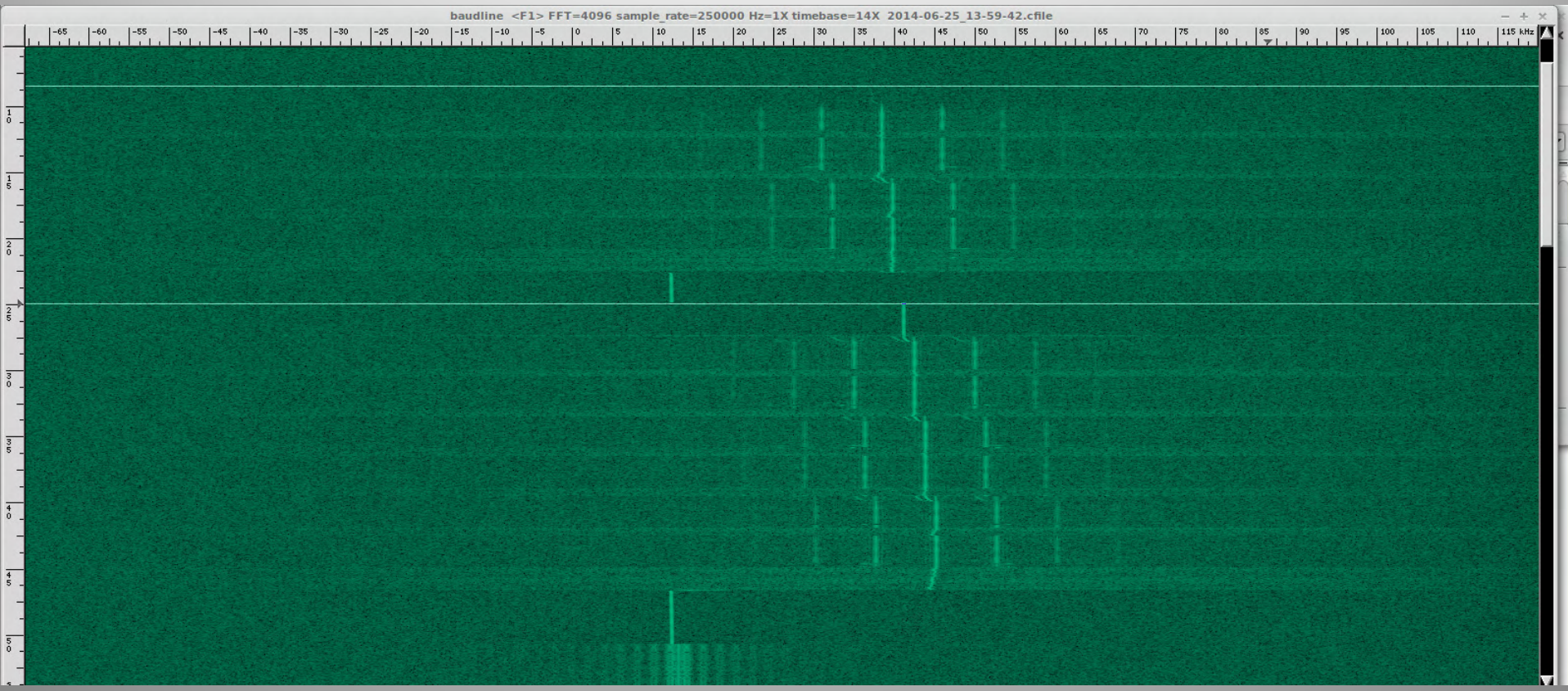
Coherent Mode & Ranging

- Enable coherent & ranging modes to determine position & velocity of probe
- Coherent mode:
  - Downlink carrier frequency will track detected uplink carrier in fixed ratio (240/221)
- Ranging mode:
  - Downlink carrier will be modulated with demodulated uplink signal
  - Can send anything up (usually tones or PN code)

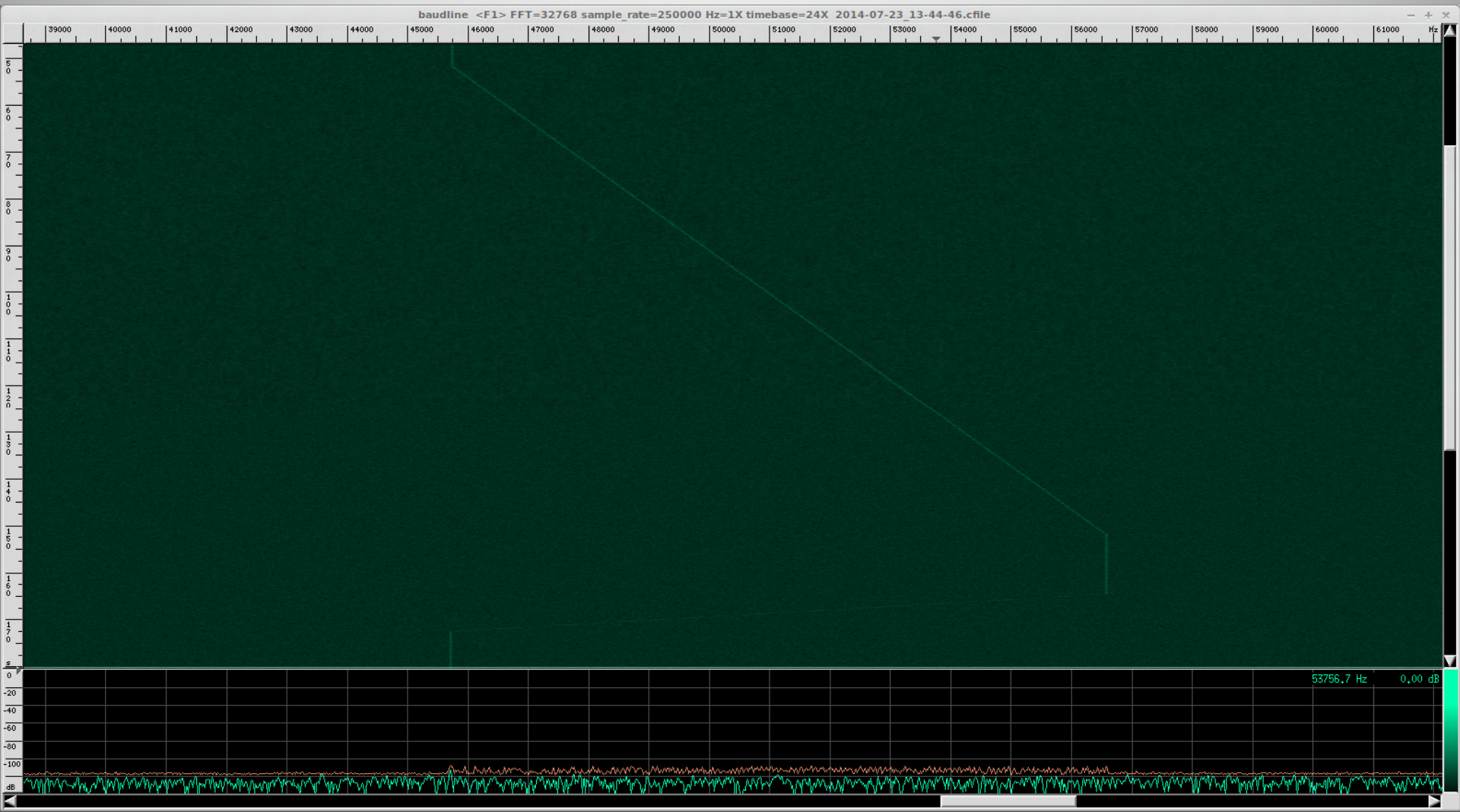
Coherent Lock



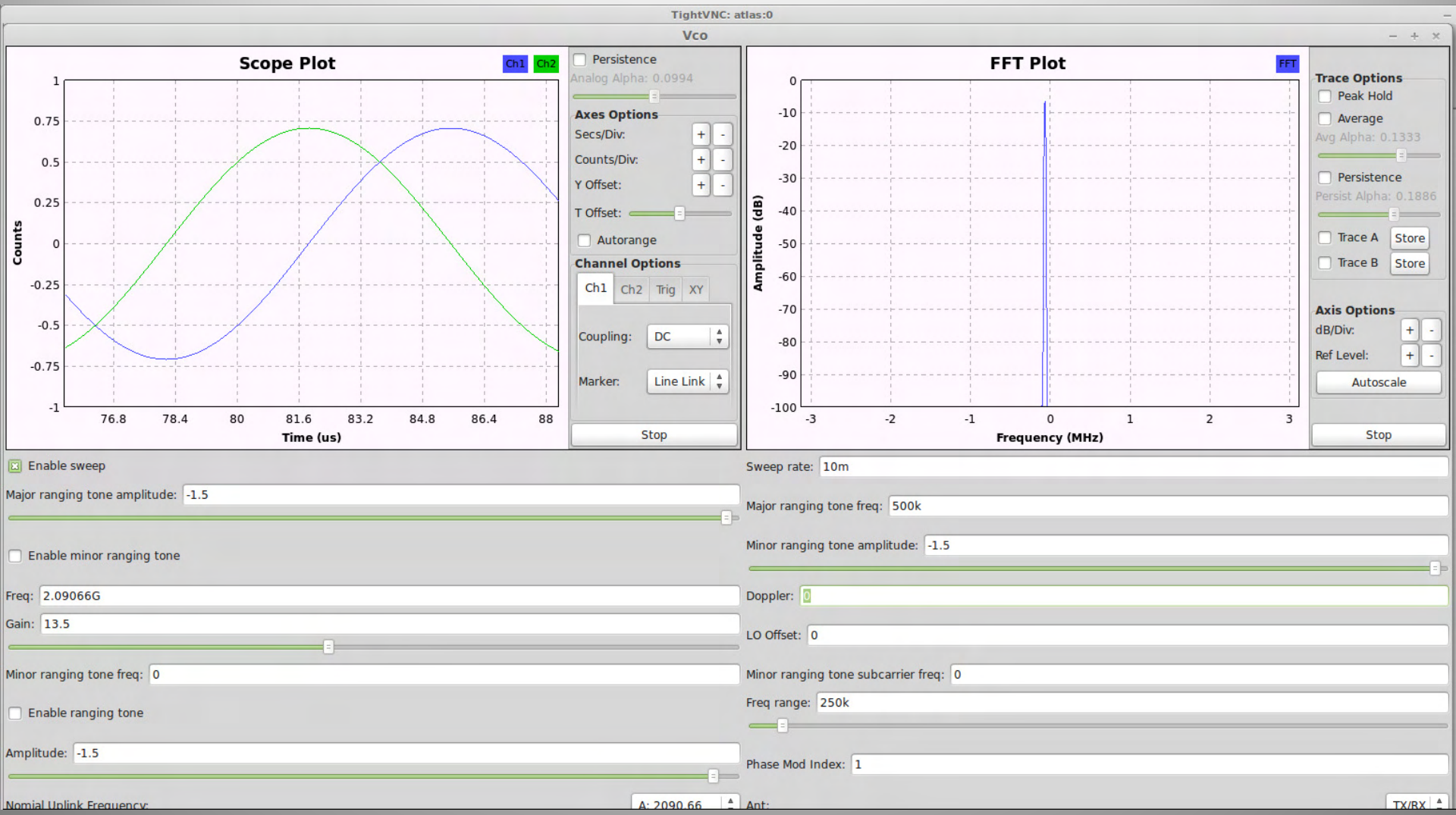
Spectrum of Downlink



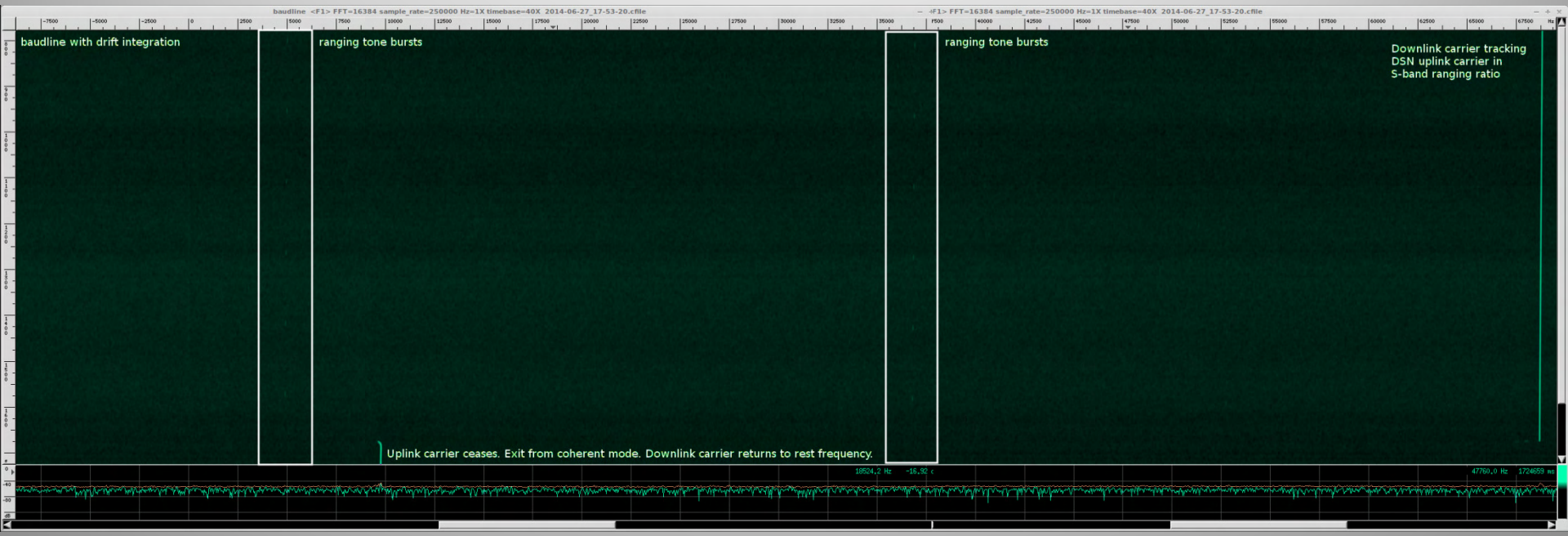
Master Blaster Sweep

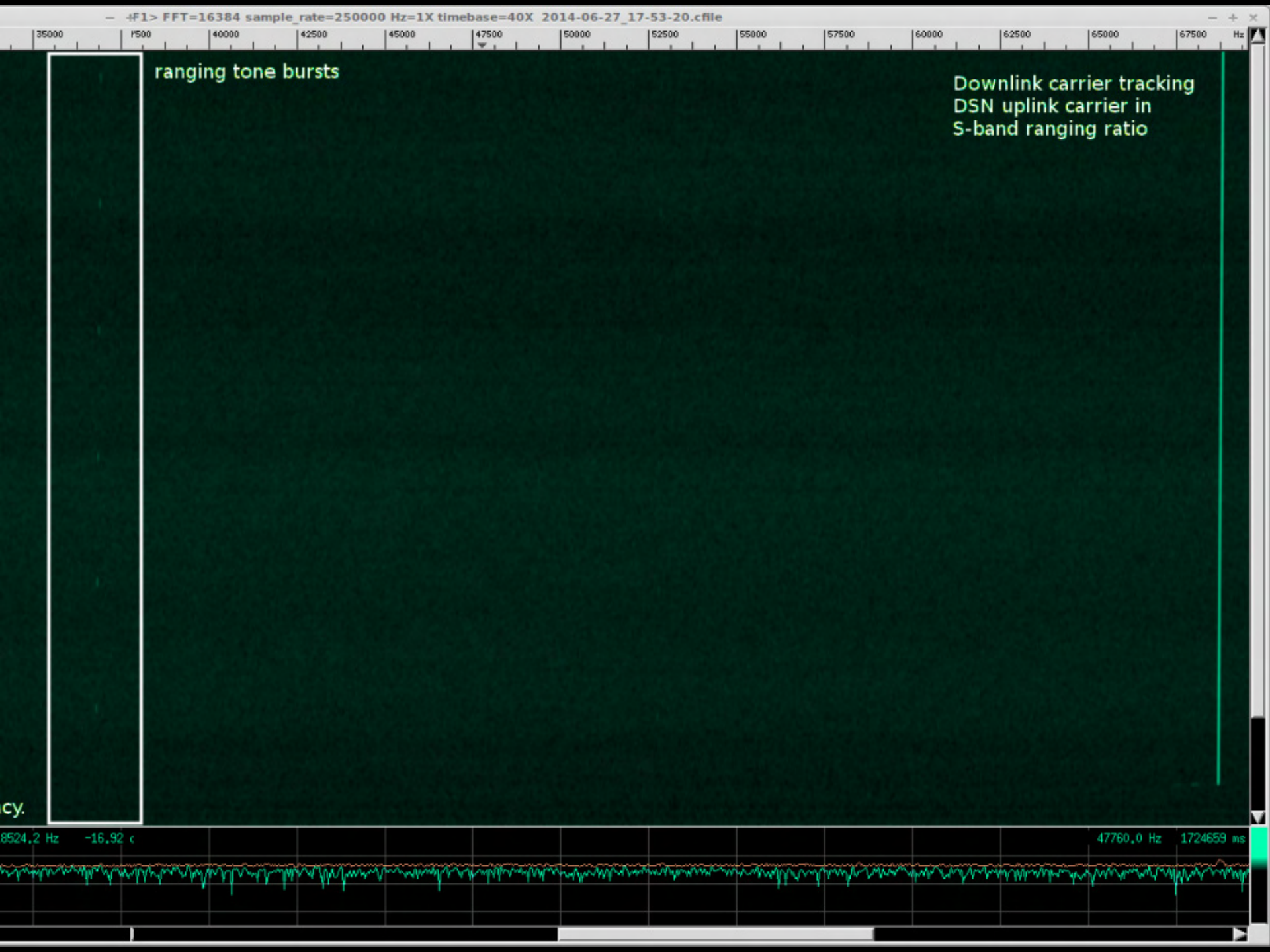


Tone Generator



Monitoring DSN Ranging




F1> FFT=16384 sample_rate=250000 Hz=1X timebase=40X 2014-06-27_17-53-20.cfile
35000
40000
42500
45000
47500
50000
52500
55000
57500
60000
62500
65000
67500
Hz
ranging tone bursts
Downlink carrier tracking
DSN uplink carrier in
S-band ranging ratio
8524.2 Hz
-16.92
47760.0 Hz
1724659 ms

Real-time Telemetry

```
000 7c  001[02]002 02  003 02  004 02  005 02  006 02  007 02  008 7c  009 02  010 02  011 02  012 02  013 02  014 02  015 02
016 7c  017 00  018 02  019 89  020 00  021 00  022 00  023 00  024 7c  025 1d  026 02  027 79  028 a4  029 00  030 00  031 00
032 7c  033 b2  034 02  035 00  036 7b  037 02  038 28  039 02  040 7c  041 79  042 02  043 76  044 0f  045 5e  046 64  047 36
048 7c  049 3a  050 02  051 76  052 00  053 02  054 e3  055 02  056 7c  057 dd  058 02  059 00  060 d7  061 45  062 23  063 47
064 7c  065 00  066 02  067 e0  068 00  069 00  070 00  071 00  072 7c  073 df  074 02  075 00  076 a0  077 00  078 00  079 00
080 7c  081 00  082 02  083 c9  084 b7  085 62  086 91  087 1d  088 7c  089 cc  090 02  091 02  092 00  093 08  094 00  095 00
096 7c  097 01  098 02  099 1d  100 00  101 85  102 84  103 02  104 7c  105 47  106 02  107 0e  108 a0  109 00  110 00  111 00
112 7c  113 0e  114 02  115 00  116 3f  117 f6  118 cb  119 9e  120 7c  121 47  122 02  123 12  124 fc  125 81  126 9f  127 be
```

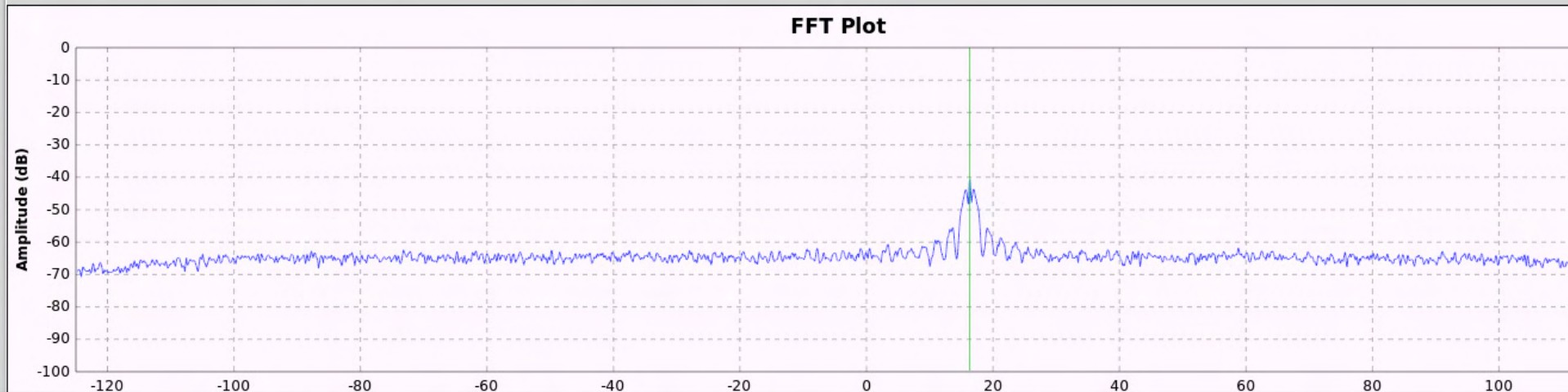
Top Block

PLL Loop BW: 10

XLate Offset: 16.4714k

XLate BW: 20.48k

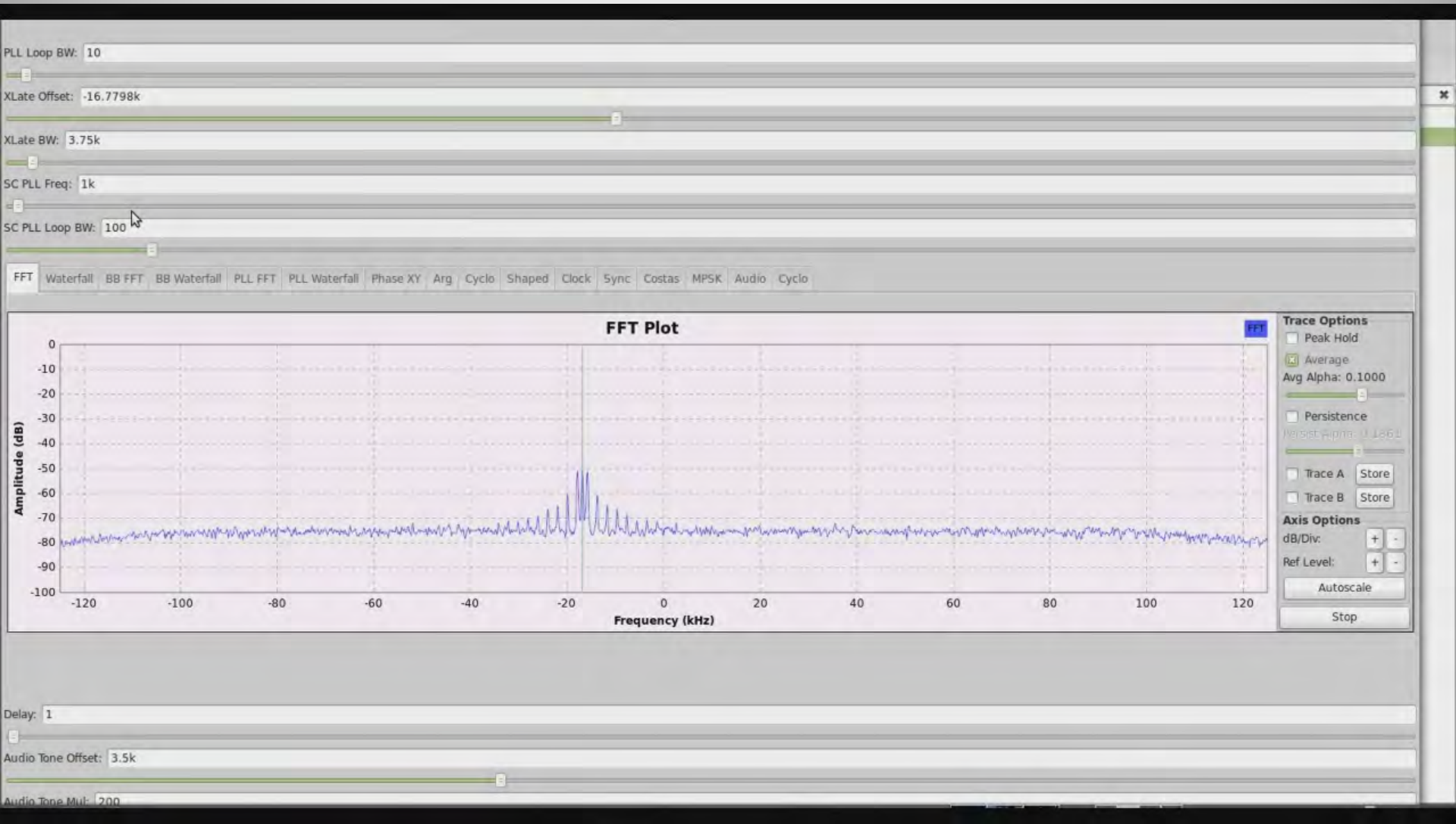
FFT | Waterfall | BB FFT | BB Waterfall | PLL FFT | PLL Waterfall | Phase XY | Arg | Cyclo | Shaped | Clock | Sync | Audio



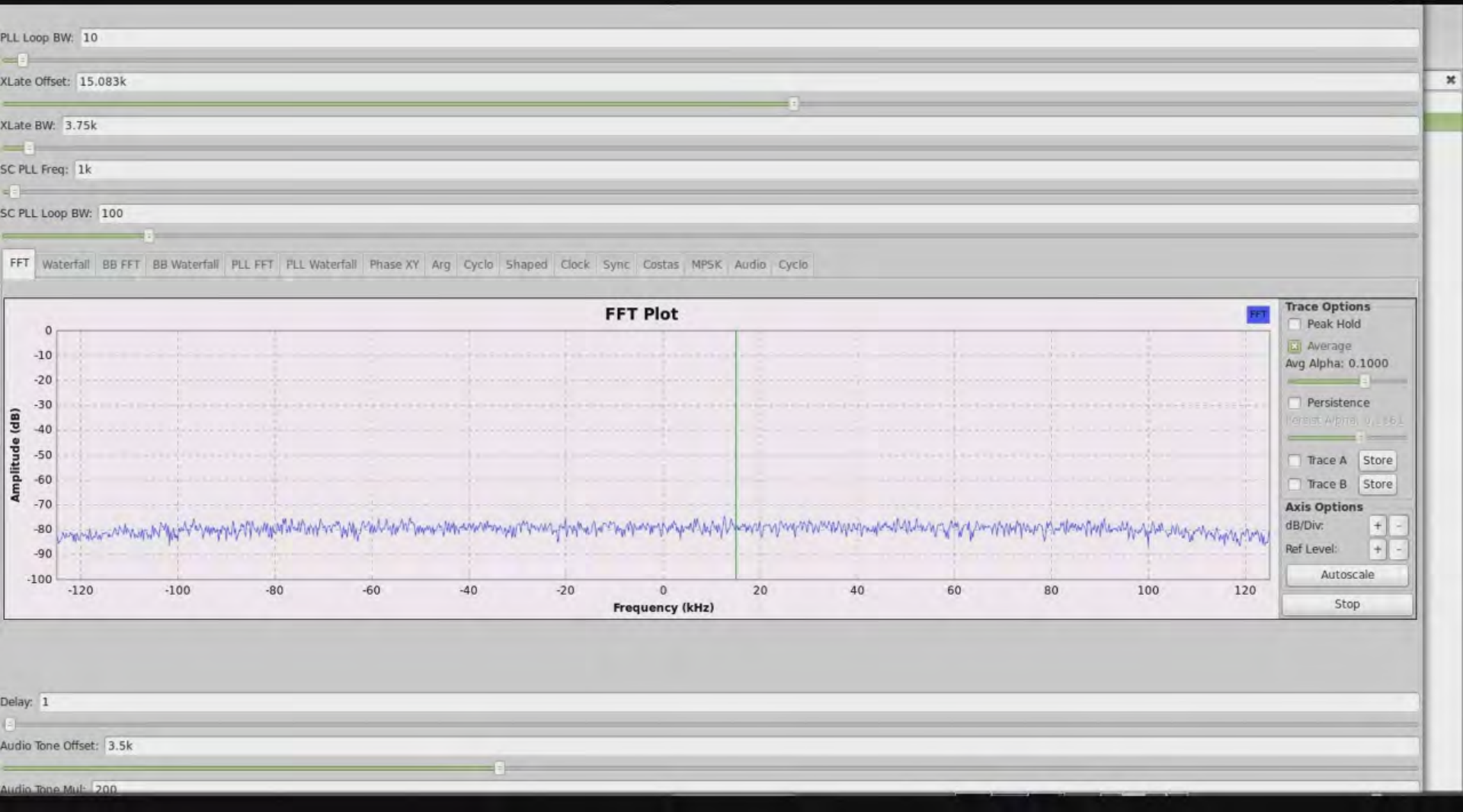
Live Telemetry from Bochum

- Many thanks to our friends at AMSAT-DL

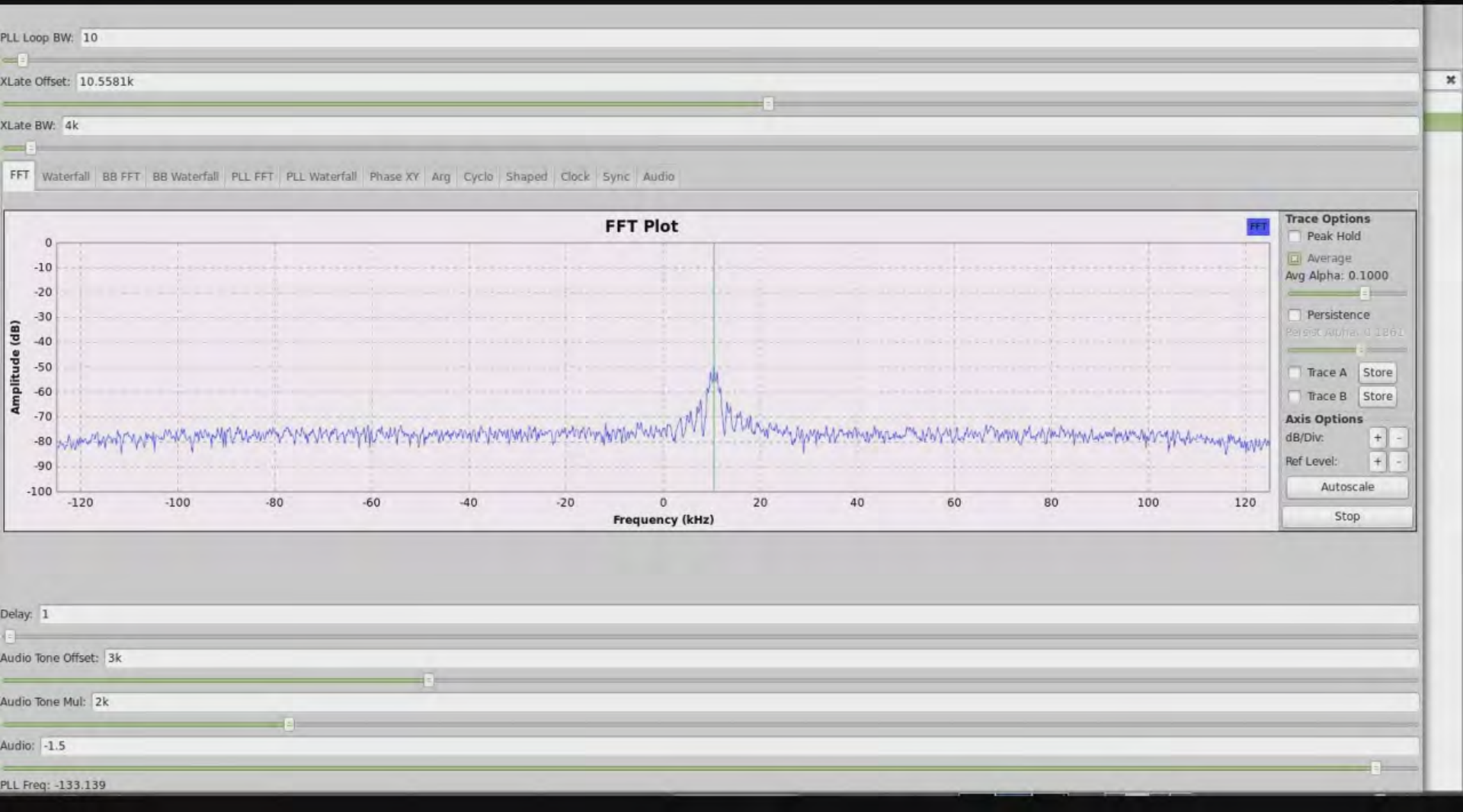
Telemetry: 16 bps



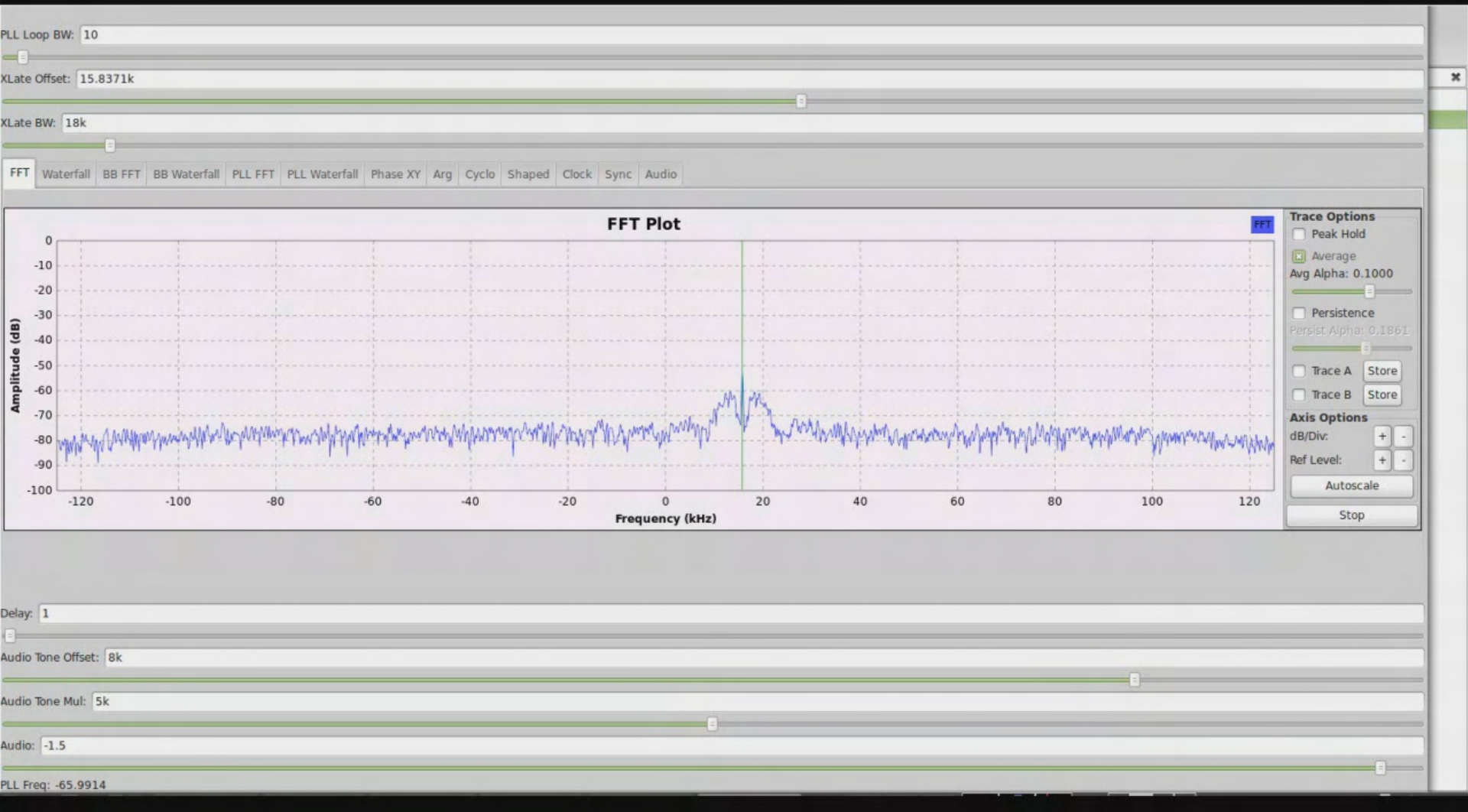
Telemetry: 64 bps



Telemetry: 512 bps



Telemetry: 2048 bps

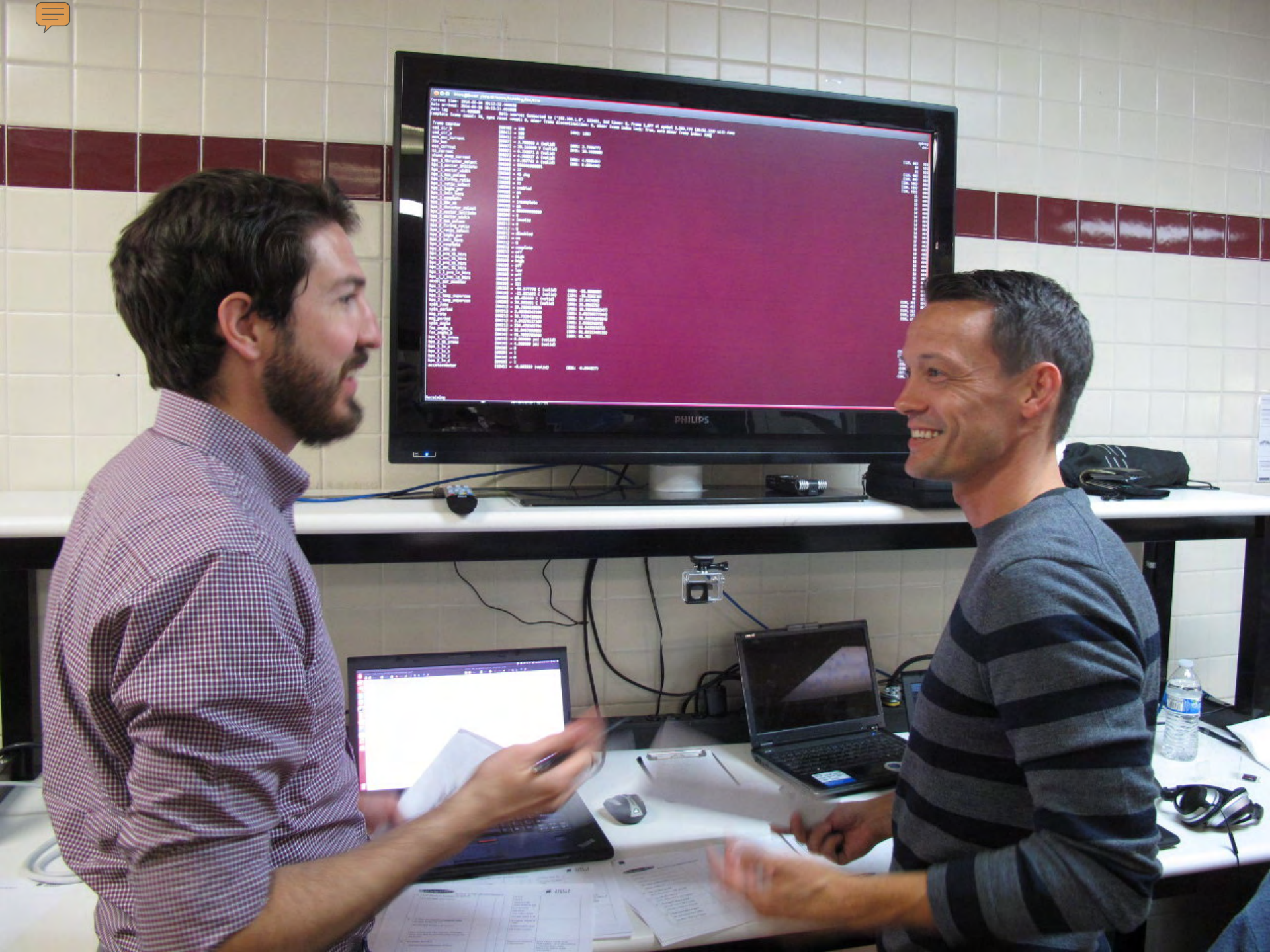


Subcoms

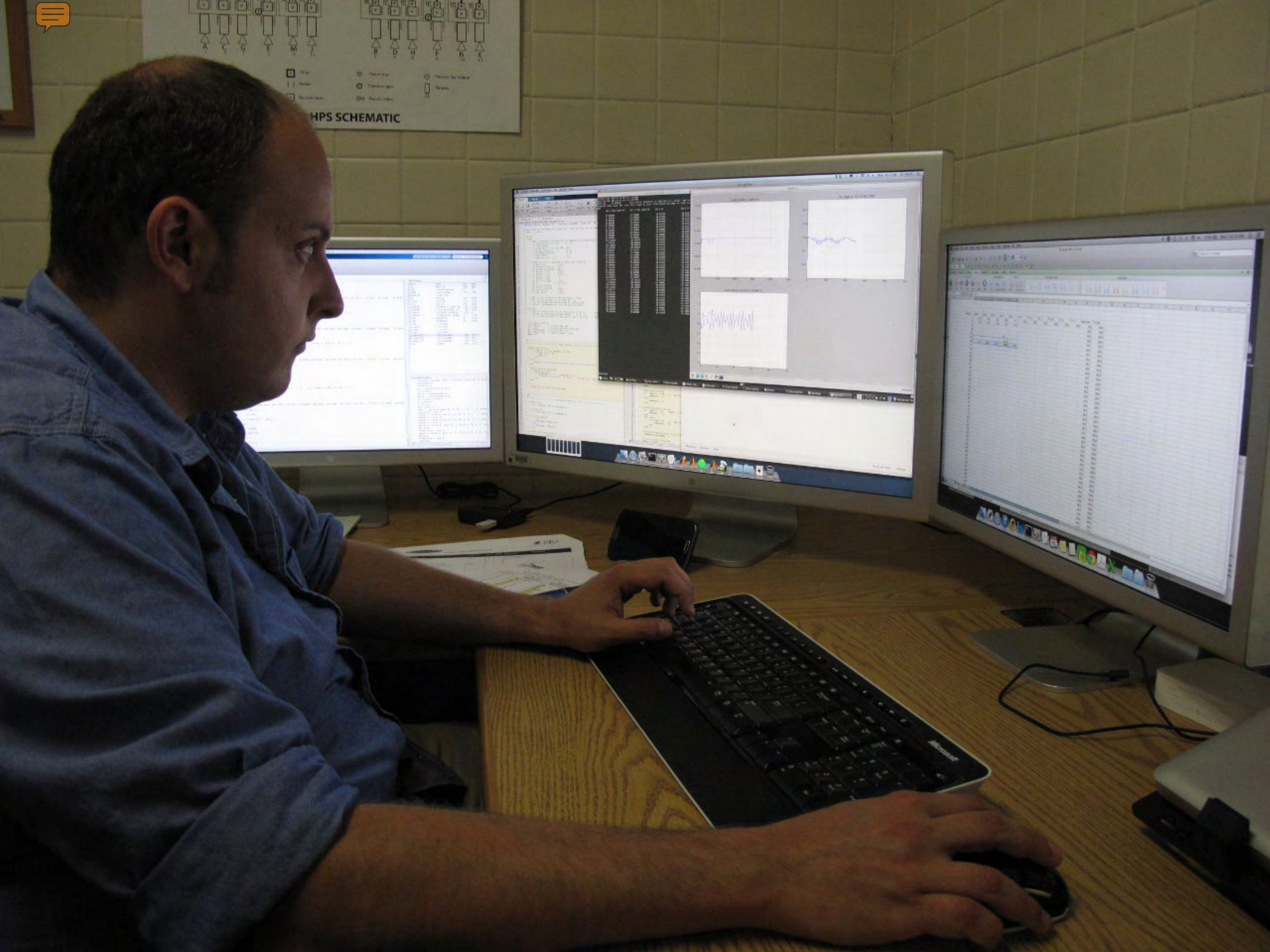
```
Current time: 2014-06-24 07:39:57.793797
Data arrived: 2014-06-24 07:39:57.794366
Data lag    : -0.000522         Data source: Rate: 1030, drops: 0000
Complete frame count: 5, sync reset count: 0, minor frame discontinuities: 0

 AS2   000 d5  001 fe  002 fb  003 79  004 36  005 23  006 ff  007 7c  008 7d  009 fa  010 f6  011 ff  012 cd  013 90  014 00  015 02

 000   016 33  017 56  018 4f  019 51  020 3a  021 00  022 5f  023 4e  024 50  025 45  026 48  027 cd  028 36  029 37  030 31  031 30

       032 9f  033 04  034 f9  035 7c  036 ff  037 00  038 6d  039 33  040 36  041 00  042 00  043 90  044 62  045 1c  046 89  047 1c

       048 00  049 27  050 74  051 77  052 e3  053 dd  054 e0  055 de  056 ca  057 cb  058 1d  059 47  060 00  061 46  062 b2  063[58]


 AS1   000 7d  001 00  002 b1  003 71  004 0a  005 00  006 00  007 00  008 ca  009 2f  010 02  011 01  012 00  013 07  014 0b  015 41

 000   016 52  017 ff  018 53  019 55  020 4c  021 50  022 4f  023[56] 024 55  025 4f  026 4f  027 0b  028 29  029 5a  030 40  031 46

       032 00  033 0c  034 0c  035 03  036 45  037 01  038 33  039 ed  040 00  041 ab  042 00  043 ff  044 8a  045 55  046 0f  047 0d

       048 02  049 08  050 31  051 07  052 00  053 00  054 47  055 00  056 47  057 ab  058 4c  059 33  060 ab  061 89  062 96  063 99


 DS    000 00  001 00  002 00  003 00  004 00  005 00  006 00  007 18  008 00  009 00  010 00  011 07  012 6e  013 09  014 f8  015 00

 000   016 00  017 00  018 00  019 0a  020 fb  021 54  022 00  023 f2  024 00  025 00  026 00  027 00  028 00  029 00  030 00  031 00

       032 63  033 f7  034 64  035 36  036 2f  037 b2  038 64  039[0c] 040 04  041 3c  042 0c  043 00  044 00  045 00  046 00  047 00

       048 13  049 00  050 00  051 04  052 fb  053 54  054 00  055 5c  056 00  057 aa  058 28  059 ff  060 ff  061 00  062 00  063 08
```

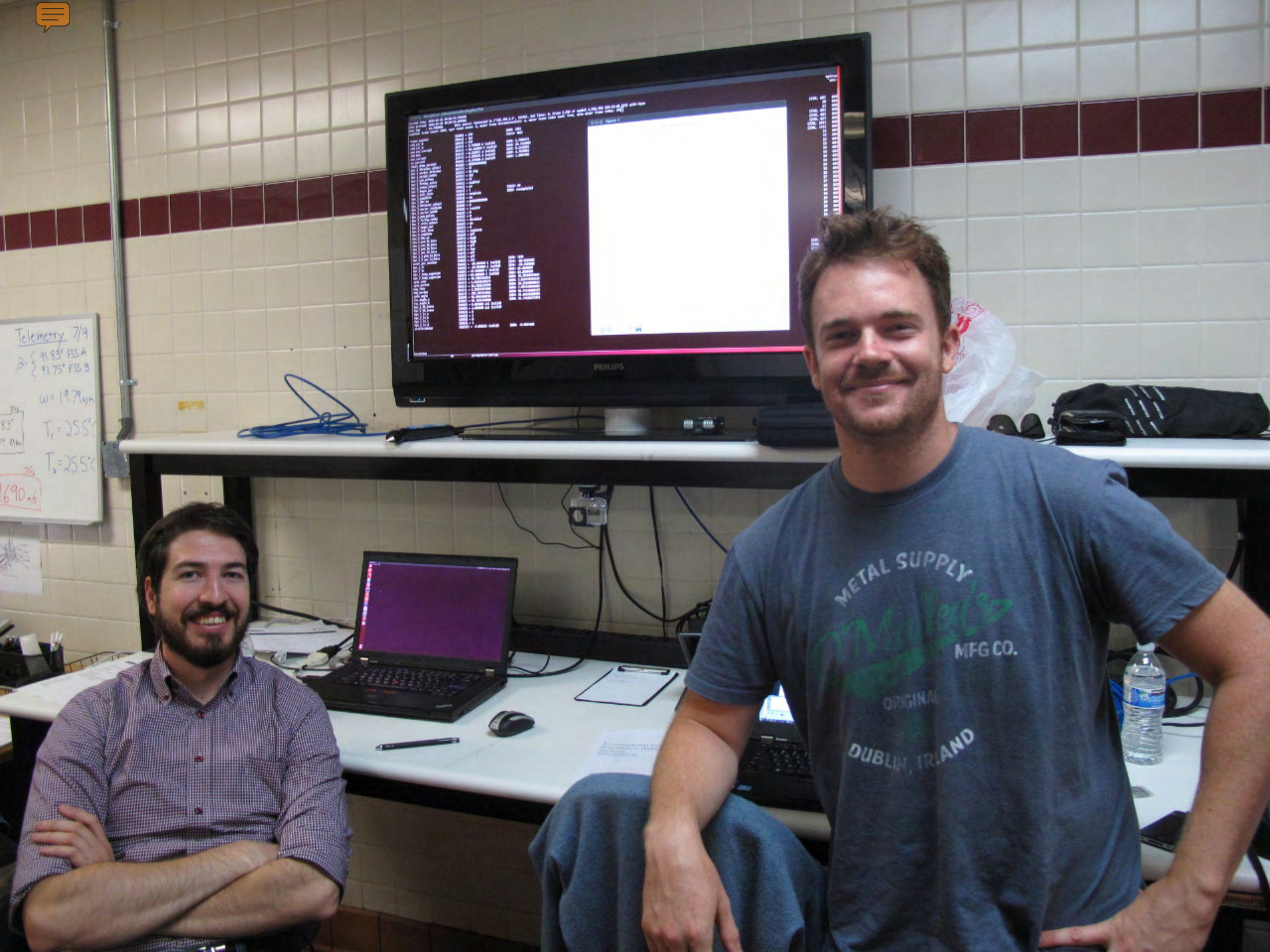
Propulsion System

```
Current time: 2014-06-24 13:50:54.153003                                                                                                spinup
Data arrived: 2014-06-24 13:50:54.161531                                                                                                `st~
Data lag    : -0.008515         Data source: Rate: 1027, drops: 0000
Complete frame count: 9, sync reset count: 3, minor frame discontinuities: 5

 frame counter                [0012] = 136                          (001: 135)                                                  (136, 60)   001
 cmd_ctr_b                    [0010] = 251                          (008: 96)                                                         20   001
 cmd_ctr_a                    [0010] = 149                          (008: 0)                                                          21   000
 non_ess_current              [0015] = 3.951613 A (valid)           (004: 3.911290)                                             (136, 85)   000
 28v_bus                      [0016] = 28.144000 V (valid)          (008: 28.136000)                                            (136, 86)   000
 ess_current                  [0015] = 0.233871 A (valid)           (002: 0.225806)                                             (136, 87)   000
 sa_current                   [0014] = 5.277778 A (valid)           (000: 5.158730)                                            (136, 101)   000
 shunt_dump_current           [0003] = 0.685484 A (valid)           (004: 0.887097)                                            (134, 121)   004
 hps_1_thruster_select        [0007] = 000000000000                 (009: 010110000110)                                               11   001
 hps_1_sector_initiate        [0007] = 475                          (009: 252)                                                        12   001
 hps_1_sector_width           [0007] = 2                            (009: 0)                                                          12   001
 hps_1_num_pulses             [0008] = 4                            (009: 2)                                                          13   001
 hps_1_firing_ratio           [0008] = 15                           (009: 1)                                                          14   001
 hps_1_ratio_select           [0008] = enabled                      (013: disabled)                                                   14   001
 hps_1_logic_pwr              [0008] = on                           (016: off)                                                        14   001
 hps_1_init_term              [0008] = 0                            (009: 1)                                                          14   001
 hps_1_complete               [0008] = incomplete                                                                                     14   001
 hps_1_28v_on                 [0008] = off                          (017: on)                                                         14   001
 hps_2_thruster_select        [0007] = 000000000000                 (009: 011111100100)                                               16   001
 hps_2_sector_initiate        [0007] = 0                            (008: 712)                                                        17   001
 hps_2_sector_width           [0007] = 0                            (008: 3)                                                          17   001
 hps_2_num_pulses             [0007] = 0                            (008: 1078)                                                       18   001
 hps_2_firing_ratio           [0006] = 0                            (015: 9)                                                          19   001
 hps_2_ratio_select           [0006] = disabled                     (015: enabled)                                                    19   001
 hps_2_logic_pwr              [0006] = on                           (008: off)                                                        19   001
 hps_2_init_term              [0006] = 0                            (015: 1)                                                          19   001
 hps_2_complete               [0006] = complete                     (008: incomplete)                                                 19   001
 hps_2_28v_on                 [0006] = off                          (008: on)                                                         19   001
 hps_1_prm_tk_htrs            [0004] = off                                                                                            55   003
 hps_1_sec_tk_htrs            [0004] = low                          (003: off)                                                        55   003
 hps_2_prm_tk_htrs            [0004] = off                          (011: low)                                                        55   003
 hps_2_sec_tk_htrs            [0004] = low                          (003: off)                                                        55   003
 hps_1_2_prm_ln_htrs          [0004] = low                          (003: off)                                                        55   003
 hps_1_2_sec_ln_htrs          [0004] = low                          (003: off)                                                        55   003
 accel_pwr_monitor            [0003] = 119                                                                                    (136, 38)   001
 hps_1_tc                     [0003] = -55.088889 C (valid)         (001: -51.600000)                                         (136, 41)   001
 hps_2_tc                     [0003] = -10.810811 C (valid)                                                                   (136, 51)   001
 hps_1_temp_supercom          [0005] = 1                            (005: 145)                                                (134, 57)   005
 hps_2_temp_supercom          [0004] = 1                            (012: 253)                                                (134, 67)   004
 spin_rate                    [0003] = 19.1595852499                                                                                35   007
 spin_period                  [0003] = 3.13159179688                                                                                35   007
 mag_rate                     [0003] = 18.7810935769                (006: 19.2120075047)                                            39   006
 mag_period                   [0003] = 3.19470214844                (006: 3.123046875)                                              39   006
 spin_angle                   [0003] = 207.686910423                (007: 0.0)                                                      35   007
 fss_angle                    [0004] = 91.6409684294                (001: Data out of expected range)                               58   001
 hps_1_tk_press               [0003] = 0.000000 psi (valid)                                                                   (136, 115)   000
 hps_2_tk_press               [0003] = 4.800000 psi (valid)                                                                   (136, 121)   000
 hps_1_lv_a                   [0004] = 0                                                                                      (134, 61)   004
 hps_2_lv_b                   [0004] = 0                                                                                      (134, 61)   004
 hps_1_lv_c                   [0004] = 0                                                                                      (134, 61)   004
 hps_2_lv_d                   [0004] = 0                                                                                      (134, 61)   004
 accelerometer                [0234] = 119                          (010: 221)                                                (137, 40)   000



Receiving
```

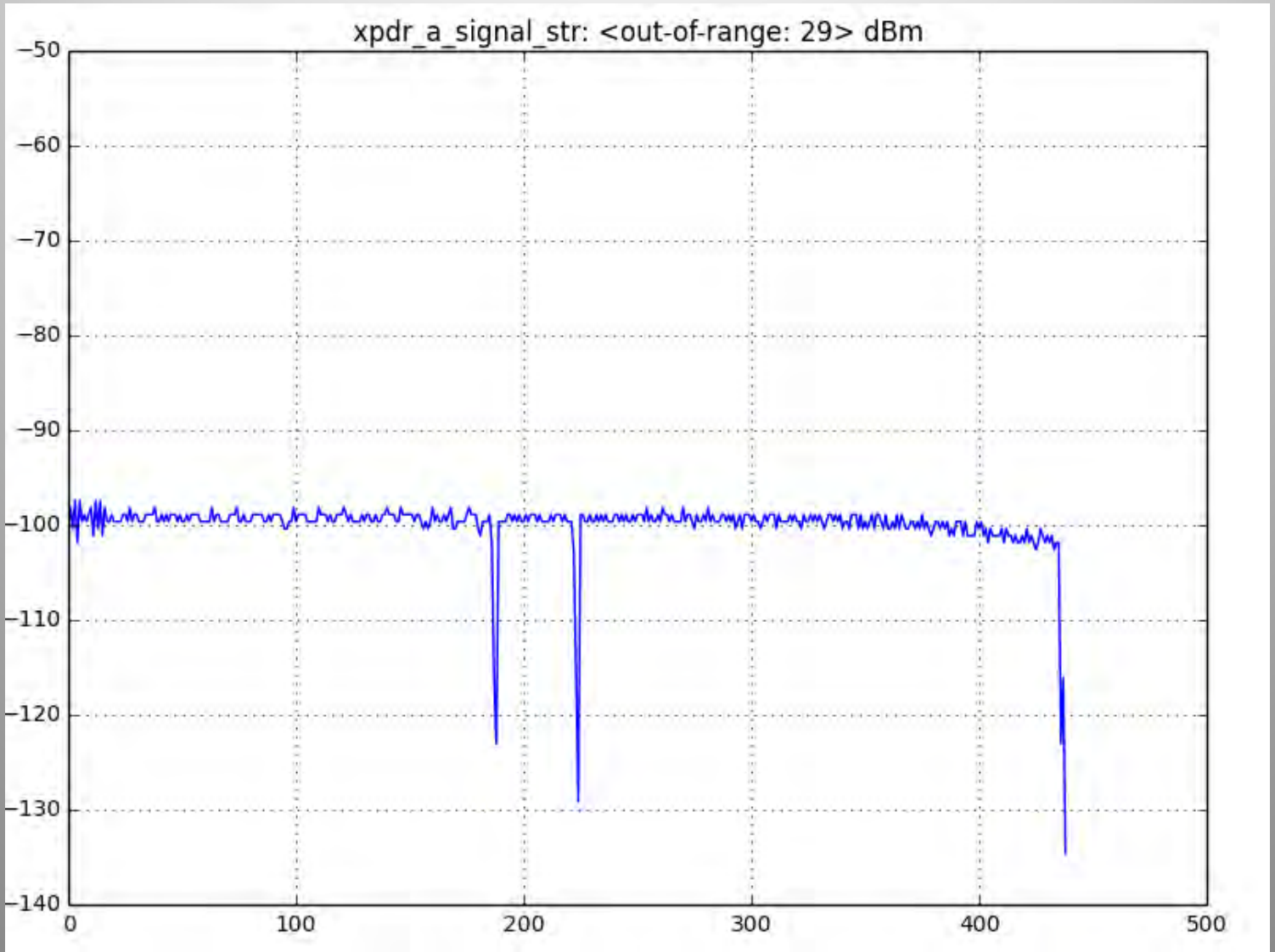

PHILIPS


SAMSUNG

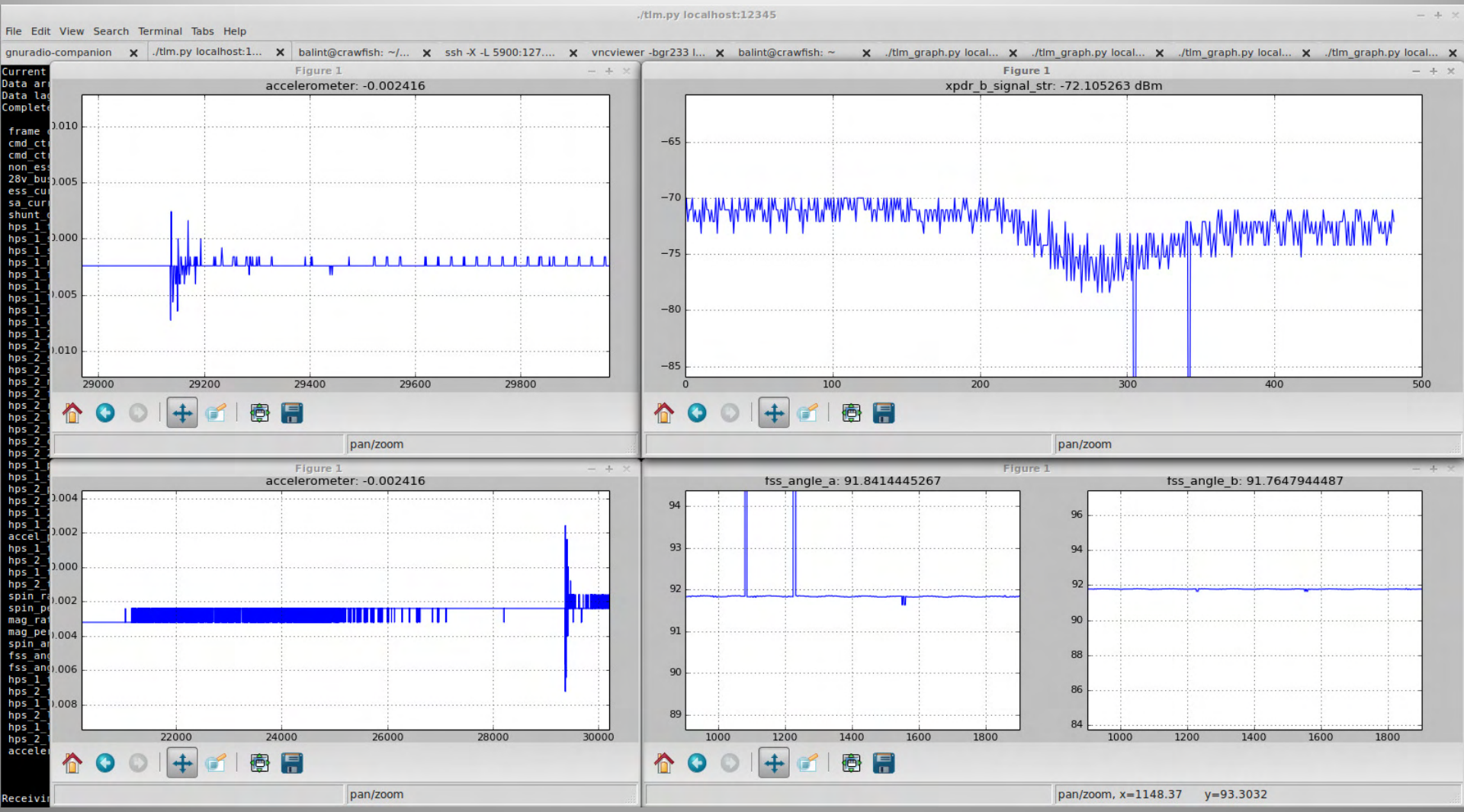

HPS SCHEMATIC


Telemetry 7/9
METAL SUPPLY
MFG CO.
DUBLIN, IRLAND

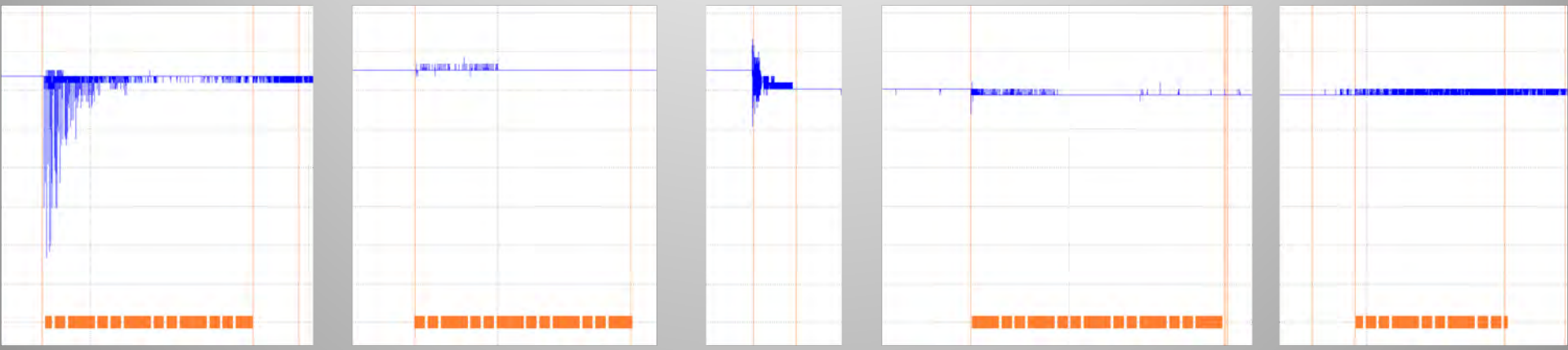
Reported Signal Strength



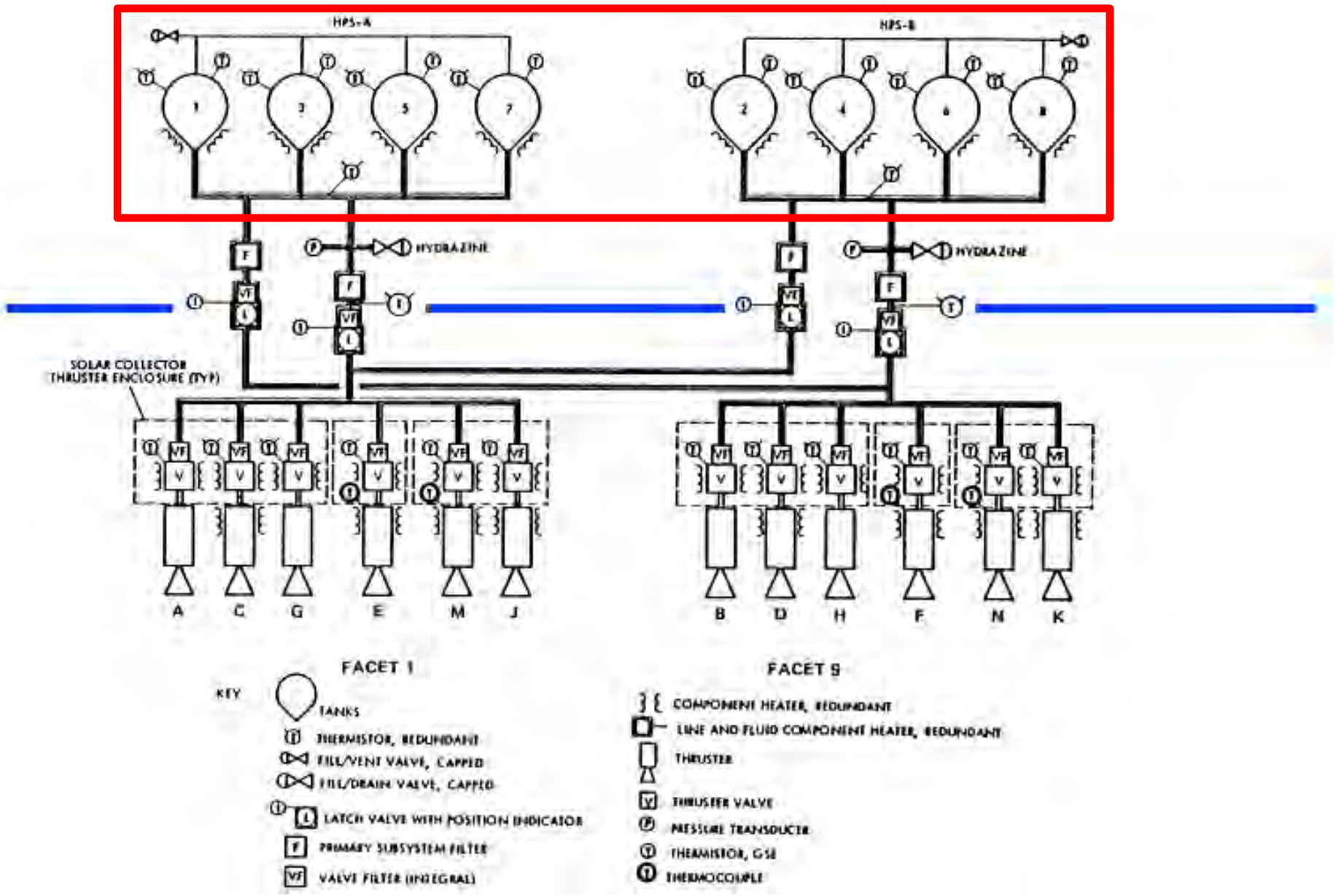
Telemetry During Thruster Firing



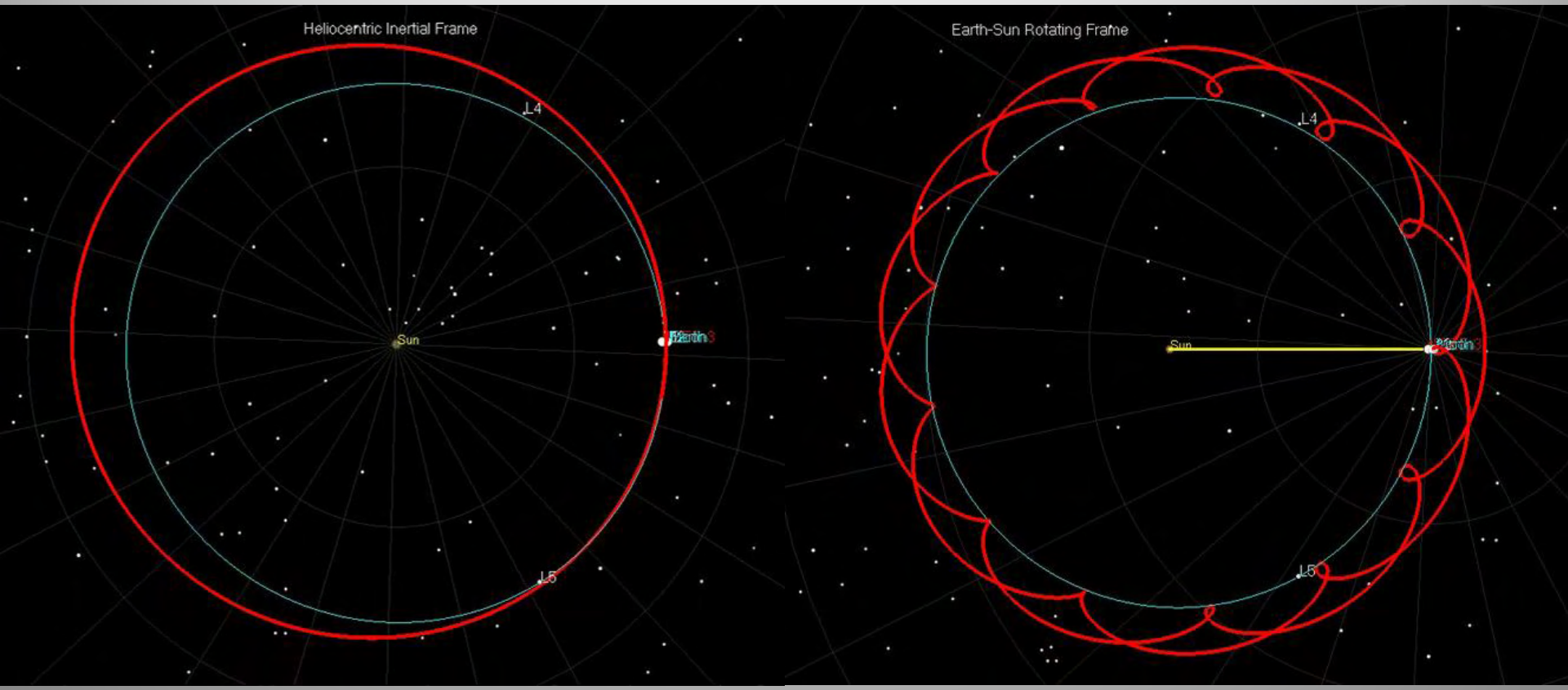
No Thrust



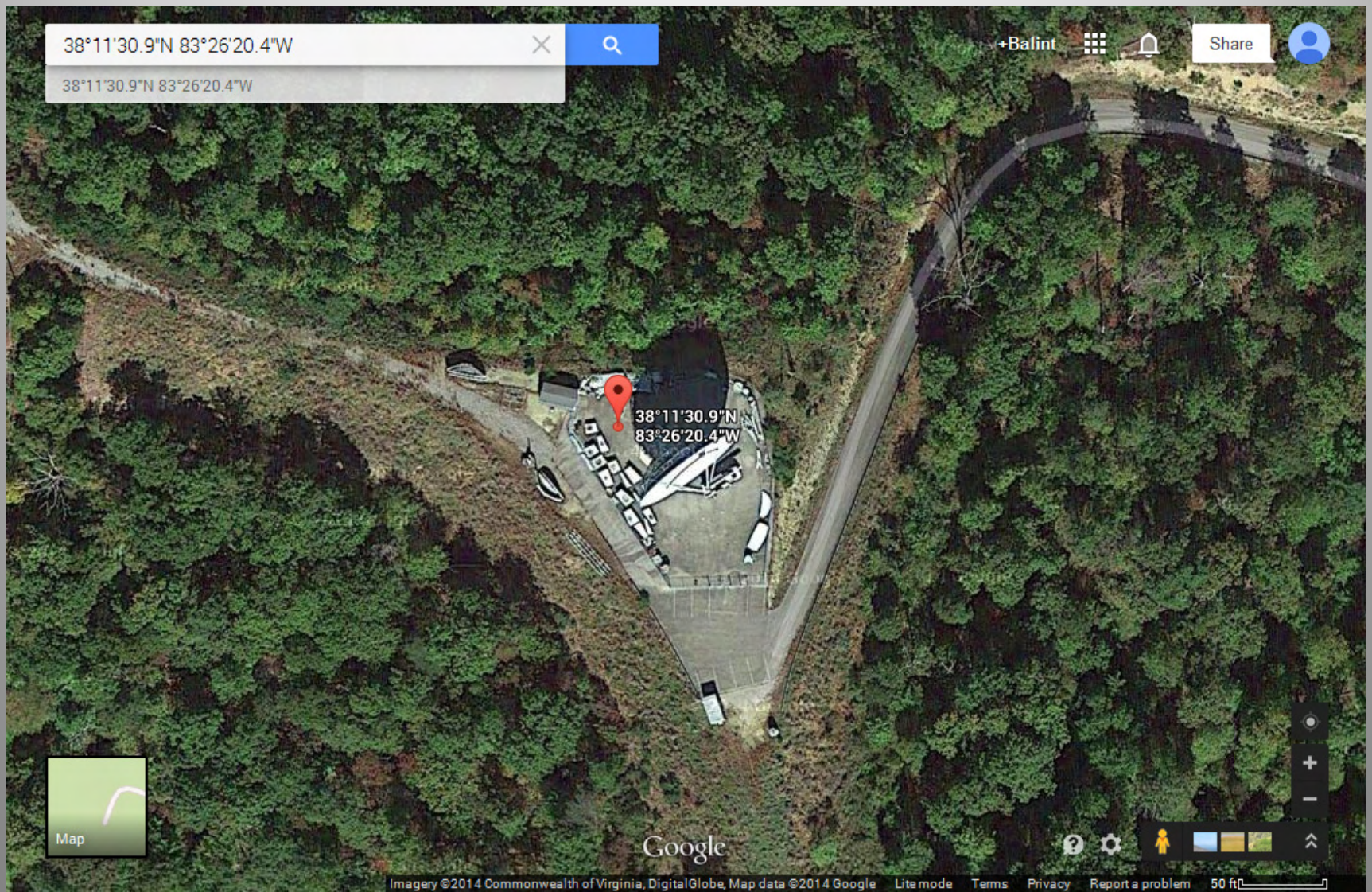
Hydrazine Propulsion System



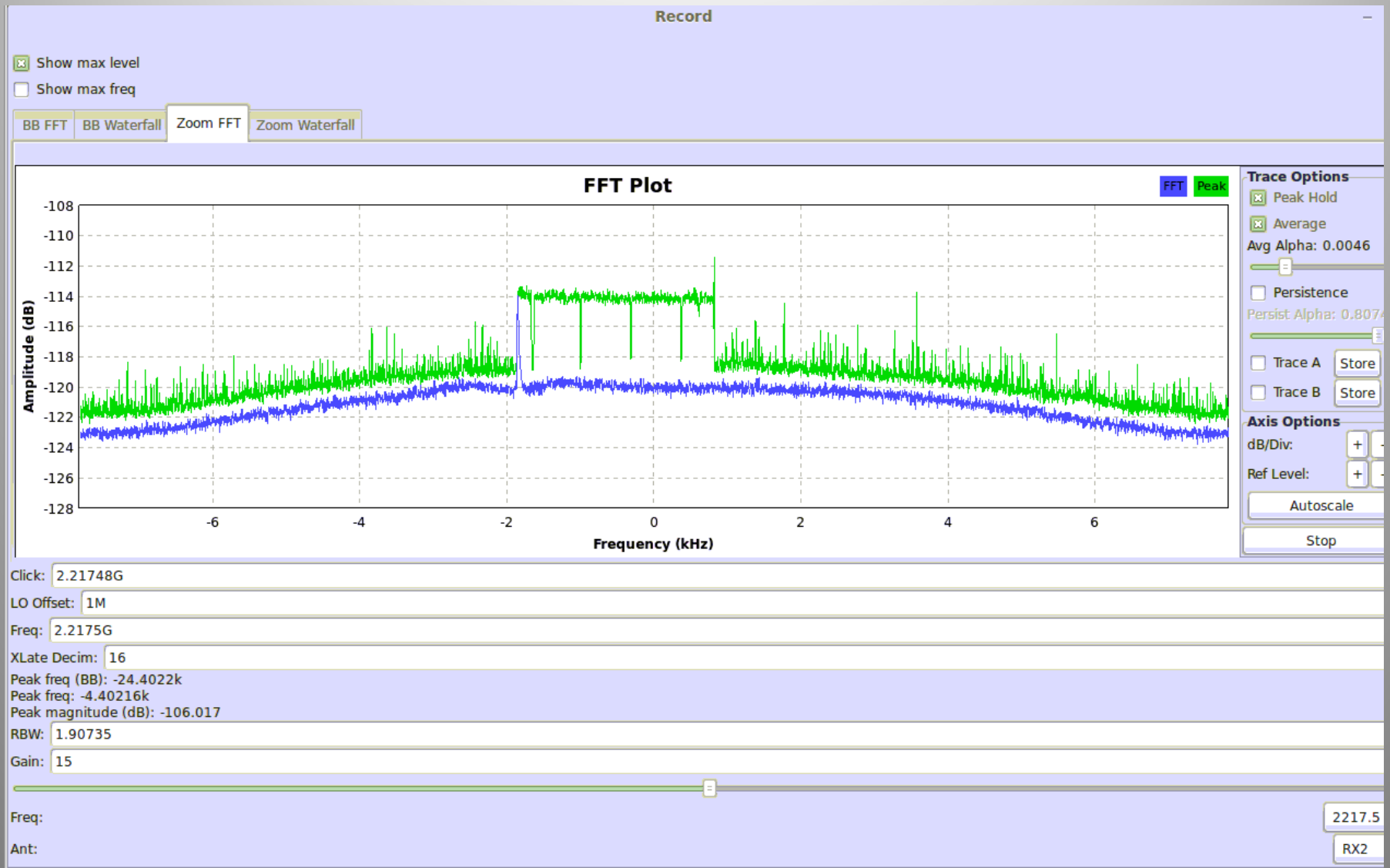
New Orbit


Heliocentric Inertial Frame
L4
Sun
Earth
L5
Earth-Sun Rotating Frame
L4
Sun
L5

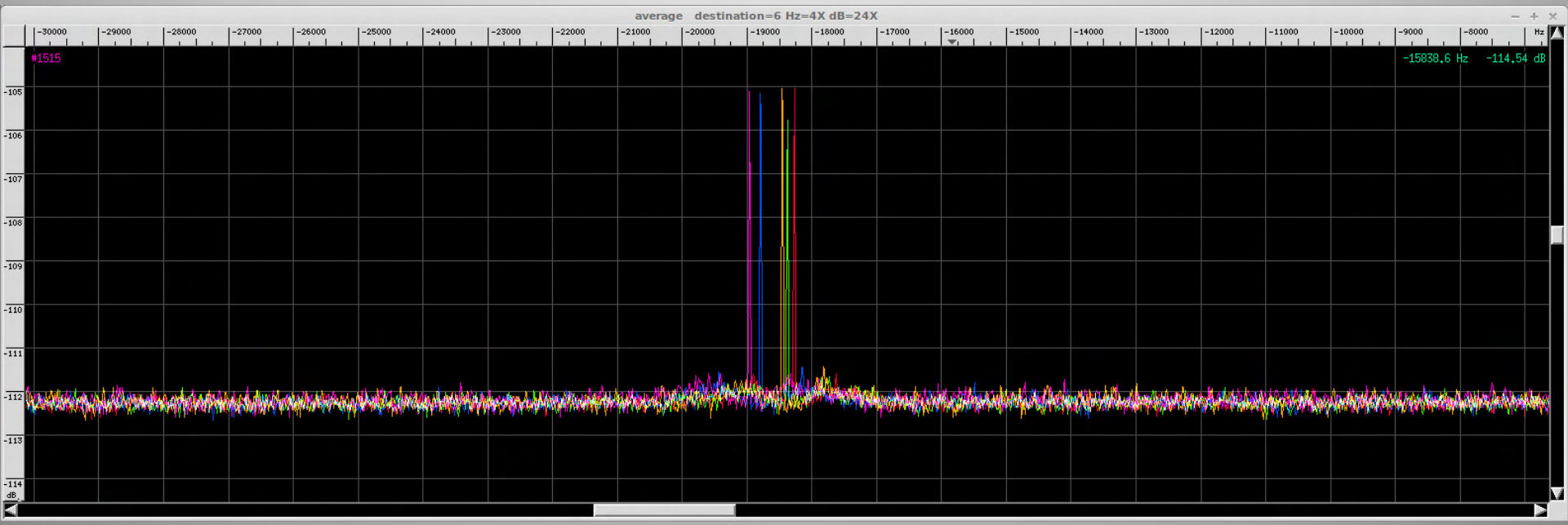
Morehead State University



Morehead: Peak Hold

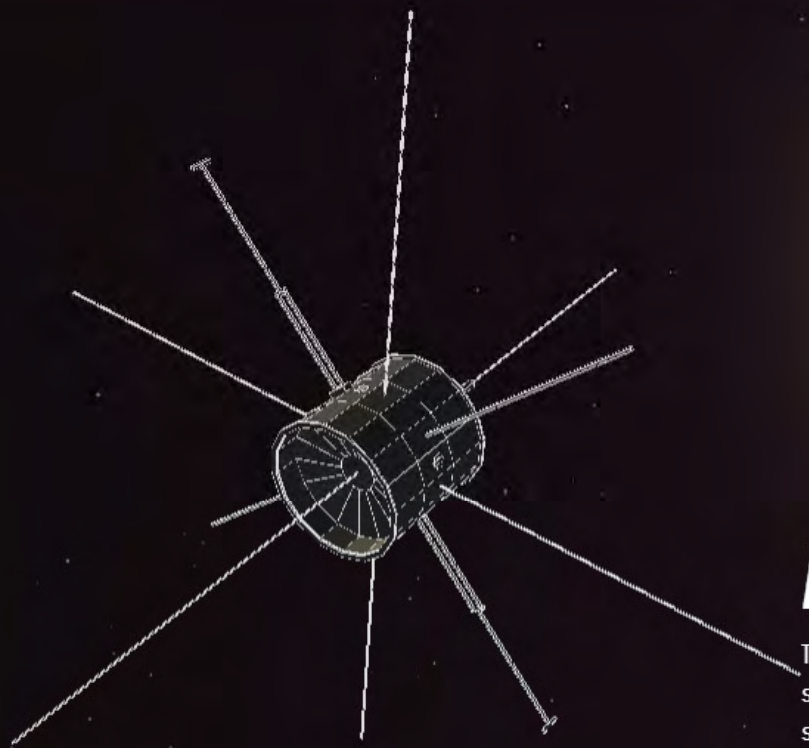


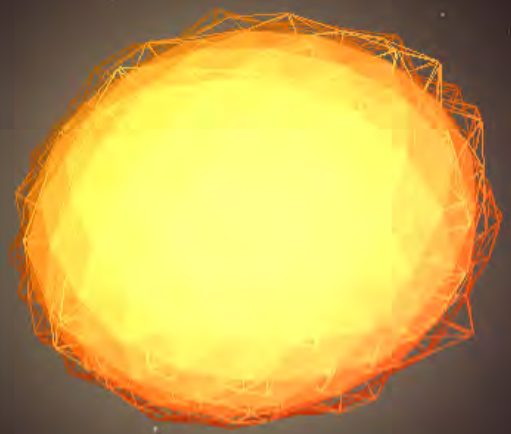
Final Days: Weak Signal



Mission Control Team

L-R: **Austin Epps** - Lead Engineer,
Jacob Gold - Systems Engineer,
Cameron Woodman - Flight Director,
Dennis Wingo - Mission Director, Project Co-lead,
Marco Colleluori - Attitude & Orbit Control Systems Engineer (and me).





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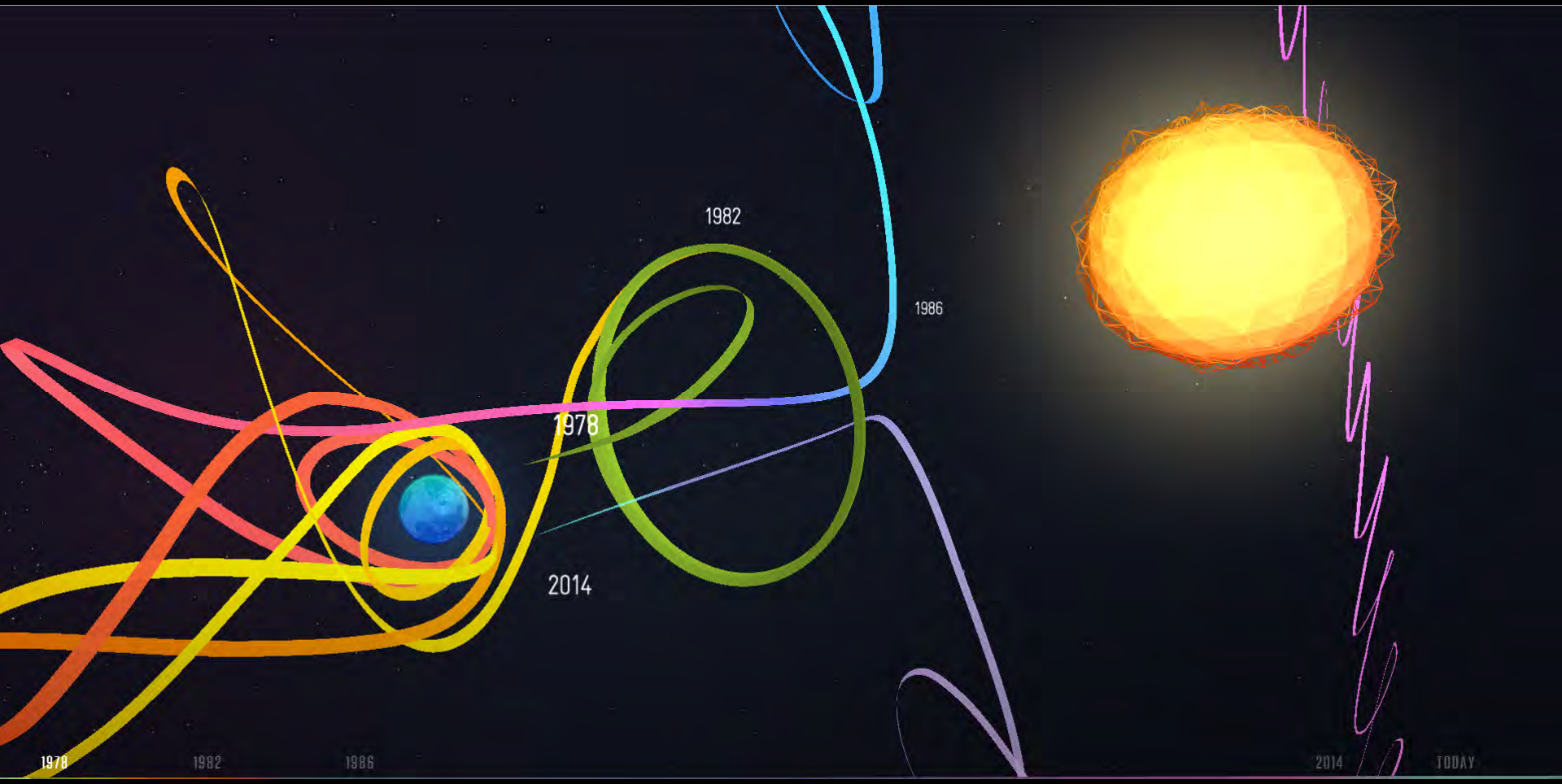

Official Sources

- http://spacecollege.org/isee3/
- http://denniswingo.wordpress.com/
- @ISEE3Reboot
- http://www.facebook.com/ISEE3Reboot

My Coverage

- http://twitter.com/spenchdotnet
- http://www.youtube.com/playlist?list=PLPmwwVknVIiUlPbkfBUY1ebP_8hA_4q8j
- http://gallery.spench.net/v/Arecibo/

More Links

- Telemetry parser/display: https://github.com/balint256/ice/
- Archived telemetry frames: http://spench.net/~balint/public/isee-3/
- Phil Karn's decoder: http://www.ka9q.net/isee.html
- John Malsbury's post about the project: http://www.jmalsbury.com/how-to-talk-to-a-36-year-old-space-probe-isee-3-with-gnu-radio-a-usrp-and-a-big-dish/

Ooops…