Ministerio del Ambiente | Instituto Geofísico del Perú - IGP | Dirección Científica | Radio Observatorio de Jicamarca

Satellite and ground-based instrumentation for TEC measurements at low latitudes

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CEDAR 2017, Keystone, CO,

Satellite and ground-based instrumentation for TEC measurements at low latitudes

Outline

- Introduction
- Motivation
- Methodology
- Transmitter
- Receiver
- Developments
- Preliminary measurements

JRO
Located at ~20 km east of Lima, Peru
(11.95º S, 76.87º W).

Jicamarca Radio Observatory (JRO)

Located at ~20 km east of Lima, Peru (11.95º S, 76.87º W).

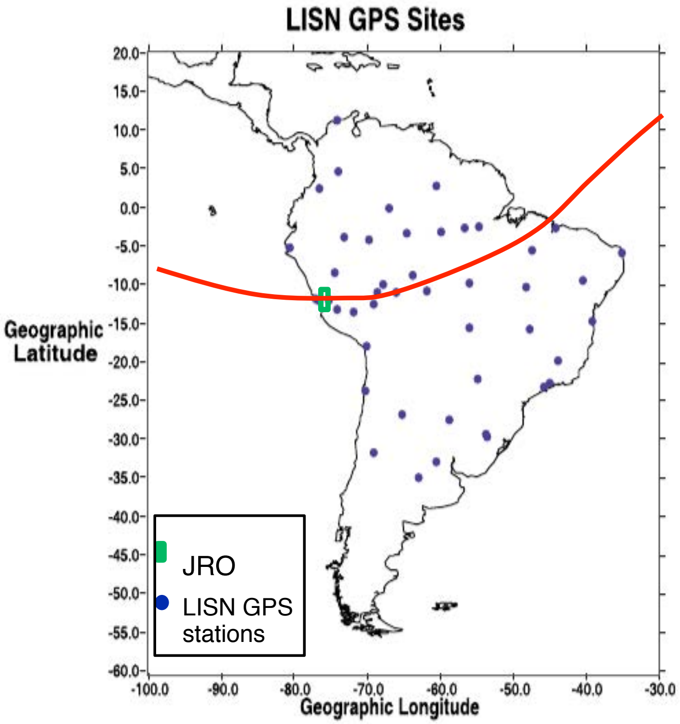
It is a research center for studies of the ionosphere and upper atmosphere.

Instituto Geofisico del Peru - Jicamarca Radio Observatory

Jicamarca Radio Observatory

•Radar measurements

•Other ground-based instruments, GPS network



- Ionospheric measurements at the magnetic equator in Peru.

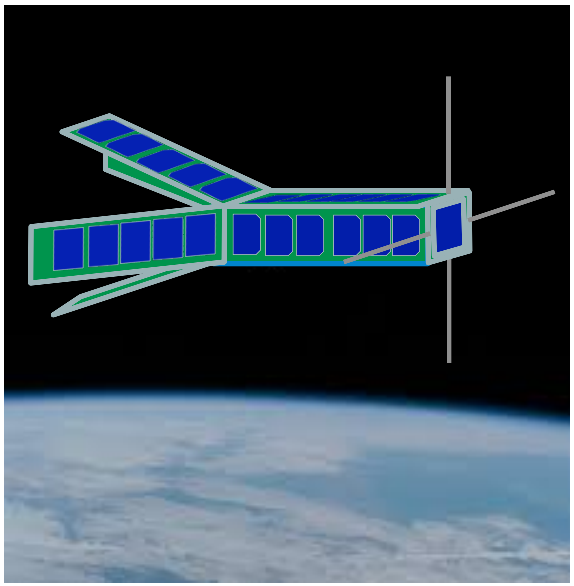
CubeSat instrumentation and ground-based receivers at the Jicamarca Radio Observatory for TEC measurements

JRO

New projects

- Using nanosatellite technology
- Satellite instrumentation
- Receiver stations
- Studies of the ionosphere
- Irregularities
- Variability

Motivation



- Obtain **TEC measurements**.
- Investigate the **ionospheric variability** by using space-based instruments in addition to the ground-based radar measurements.
- Detect **irregularities**, spread F that affect communications and navigation signals.
- Combination with **Jicamarca measurements**.
- Extend network of receivers.
- Latitudinal and Longitudinal variability.

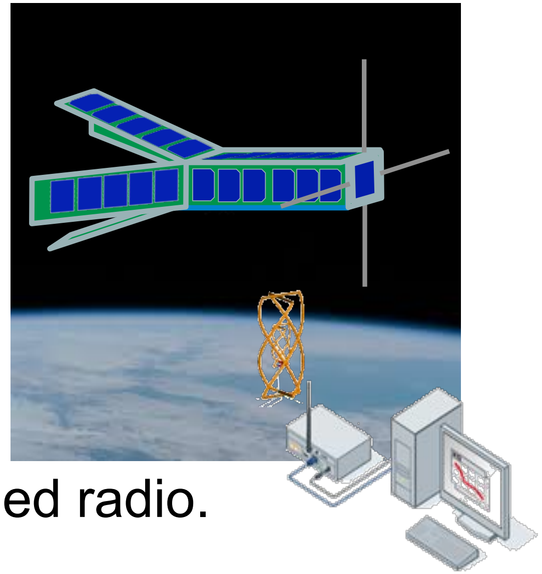
Space-based instruments

- New contribution:
  - Develop Radio beacon instrumentation for cubesats for TEC measurements.
  - First Peruvian satellite instrument for ionospheric research.

  - Development phase

Methodology

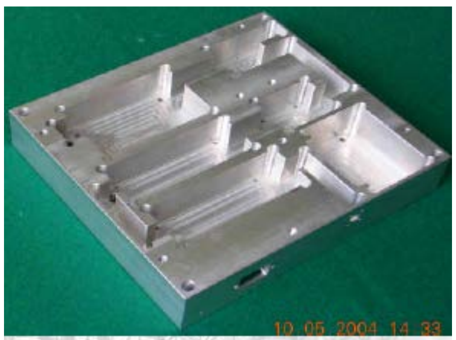
- Develop a nanosatellite radio beacon for Low Earth Orbit ~ 600 - 800 km.
  - 2 frequencies VHF, UHF.
    150, 400 MHz
  - Coherent signals.



- Develop a ground-based receiver.
  - Digital receiver based on software-defined radio.

Previous experience: Radio Beacon for rockets at Jicamarca

NASA EQUIS II
Kwajalein
campaign



- PERSEUS
- EQUIS II
- Sounding rocket campaign

Radio Beacon installed on the rocket for EQUIS II.

Radio Beacon for rockets at Jicamarca

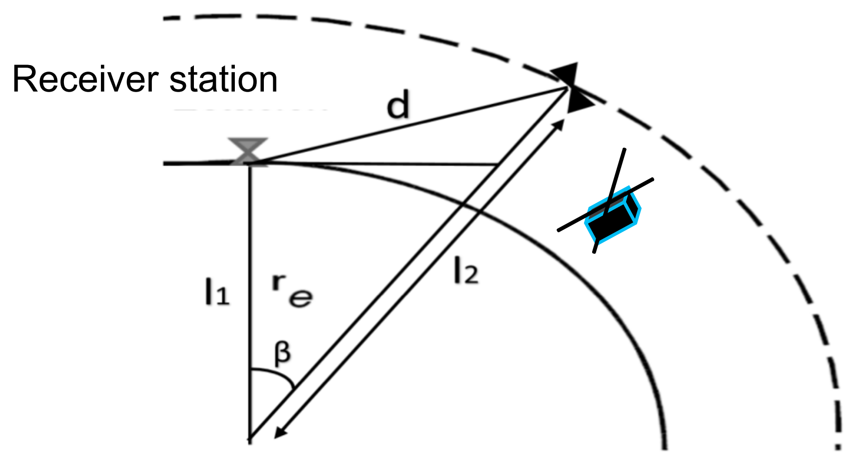
Terrier Orion Rocket with the radio beacon developed at JRO onboard before launch

NASA Launches
Aug 7, 2004
Aug 14, 2004
Sept 7, 2004
Sept 17,2004

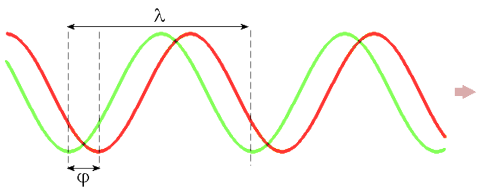
Radio Beacon for rockets at Jicamarca NASA EQUIS II

Measurements with satellites at JRO

- TEC can be used for studies of radio wave propagation and by combining several TEC measurements we can obtain an overall description of the ionization in the ionosphere to investigate its spatial and temporal variability and the occurrence of ionospheric irregularities.
- Origin spread F, conjugate phenomena.



TEC measurements



- Phase difference method
- Equations

$$\Delta\phi_f = \frac{\phi_1}{q_1} - \frac{\phi_2}{q_2} = \frac{80.6\pi N_T}{cf_0}\left(\frac{1}{q_1^2} - \frac{1}{q_2^2}\right) = \frac{8.447\times10^{-7} N_T}{f_0}\left(\frac{1}{q_1^2} - \frac{1}{q_2^2}\right) \text{ rad}$$

- Differential phase $\Delta\phi_f$ measures the time delay by comparing the phases ϕ_1 and ϕ_2 of two signals on widely separated frequencies $f_1 = q_1 f_0$, and $f_2 = q_2 f_0$ when they are translated to a common reference frequency f_0.
- N_T is total electron content TEC along the path.

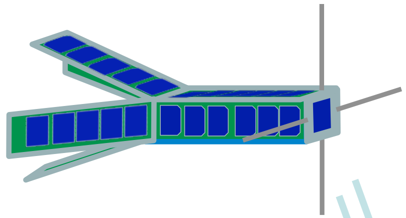
Radio beacons and receivers

Requirements
•Transmission power> batteries and solar panels.
•The physical dimensions of the transmitter and its control system need to be adapted to the size allowed by the nanosatellite.
•Antennas -> maximum gain and a stable link between the transmitter and receiver.

Cubesat Radio Beacons
•This type of space instrument require special considerations to operate on nanosatellites mainly due to restrictions of space, energy and weight.
•By developing radio beacons that can satisfy the technical requirements of nanosatellites it is possible to develop new missions for obtaining TEC measurements in the ionosphere with a constellation of nanosatellites.

Main Concept

Power Tx ~ 1 W



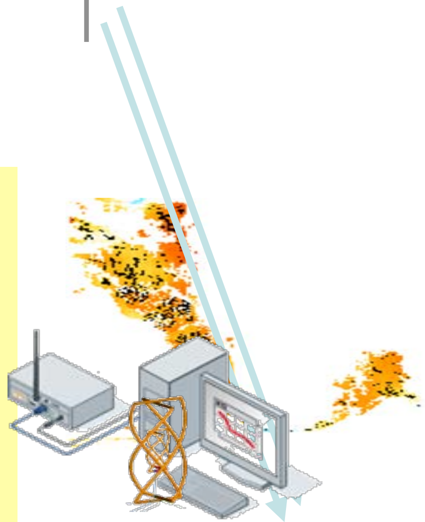
Transmitter frequencies:

VHF	UHF
150 MHz	400 MHz

Methodology:

The phase difference between the two received frequencies provides the information of total electron content along the line-of-sight between the receiving station and the space vehicle at any given instant.

[Bernhardt and Siefring, 2006].



Radio waves emitted by the transmitter onboard the CubeSat will be received by ground-based stations.

TEC will be obtained after processing the signals received by detecting the phase difference of the received radio waves.

Receivers based on Universal Software Radio Peripheral (*USRP*) [Yamamoto, 2008].

The power loss as a function of the distance and frequency is expressed by the free space loss (FSL) as shown in equation

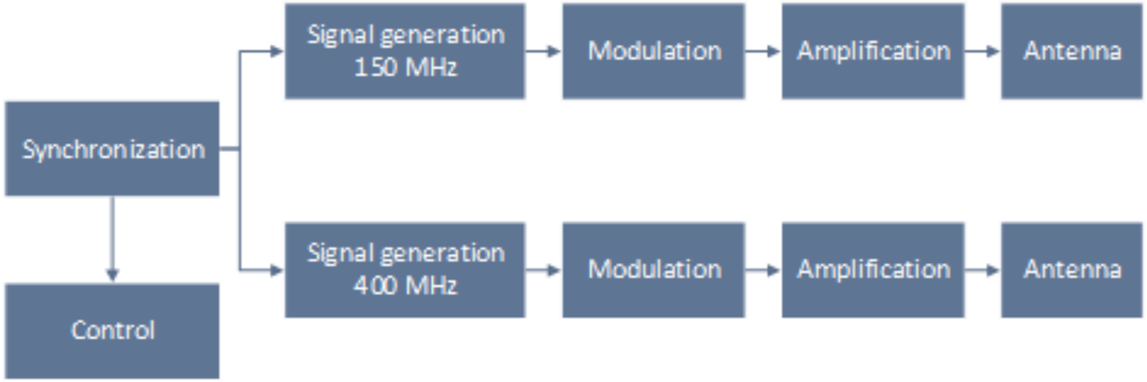
$$L_{bf} = 32{,}4 + 20Log(f) + 20Log(d)$$

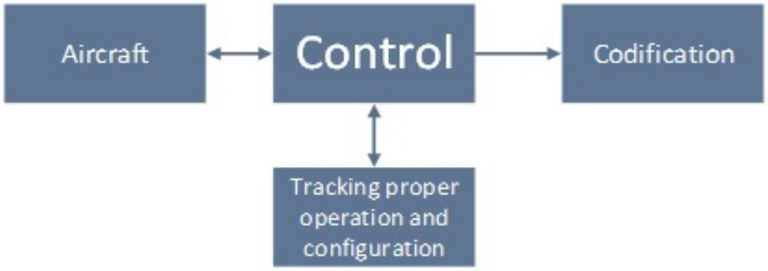
Elevation Angle (phi°)	Satelite Distance (Km)	$L_{bf(dB)}$ - 400Mhz	$L_{bf(dB)}$ - 150Mhz	Signal Level(dB) 400MHz	Signal Level (dB) 150MHz
10.92	2692	153.04	144.52	-124.04	-115.52
13.18	2529	152.50	143.98	-123.50	-114.98
15.66	2367	151.93	143.41	-122.93	-114.41
18.38	2208	151.32	142.80	-122.32	-113.80
21.41	2051	150.68	142.16	-121.68	-113.16
24.81	1897	150.00	141.48	-121.00	-112.48
28.67	1748	149.29	140.77	-120.29	-111.77
33.1	1605	148.55	140.03	-119.55	-111.03
38.23	1469	147.78	139.26	-118.78	-110.26
44.22	1343	147.00	138.48	-118.00	-109.48
51.22	1231	146.25	137.73	-117.25	-108.73
59.36	1136	145.55	137.03	-116.55	-108.03
58.69	1063	144.97	136.45	-115.97	-107.45
79.04	1016	144.58	136.06	-115.58	-107.06

Where *d* is the distance in km between the transmitter and the receiver, and *f* is the signal frequency in MHz. We can calculate the distance *d* knowing the satellite position and the ground-based station receiver position assuming a circular orbit.

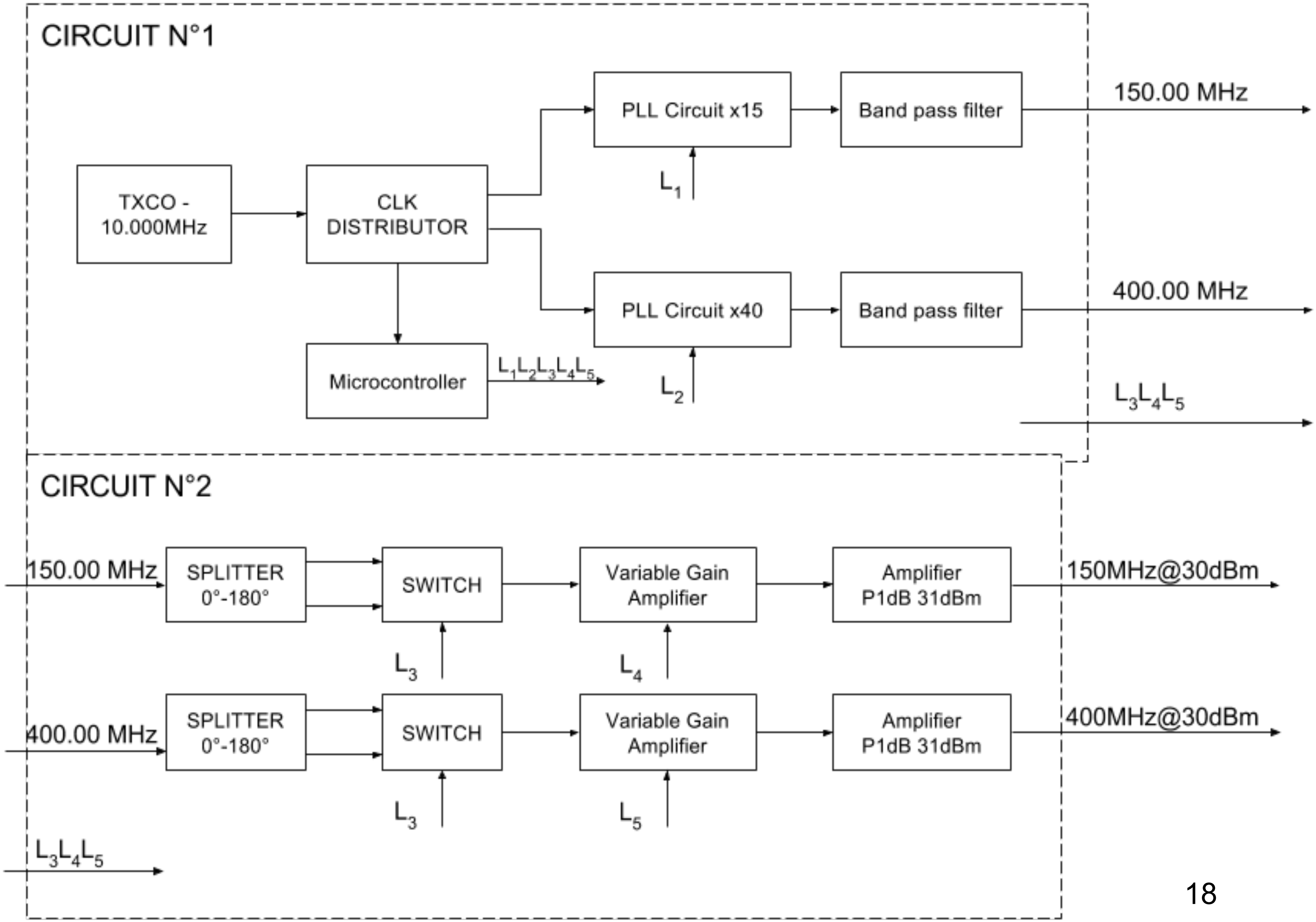
Transmitter Block Diagram

General overview





Transmitter Block Diagram



PTx = 1.0 W

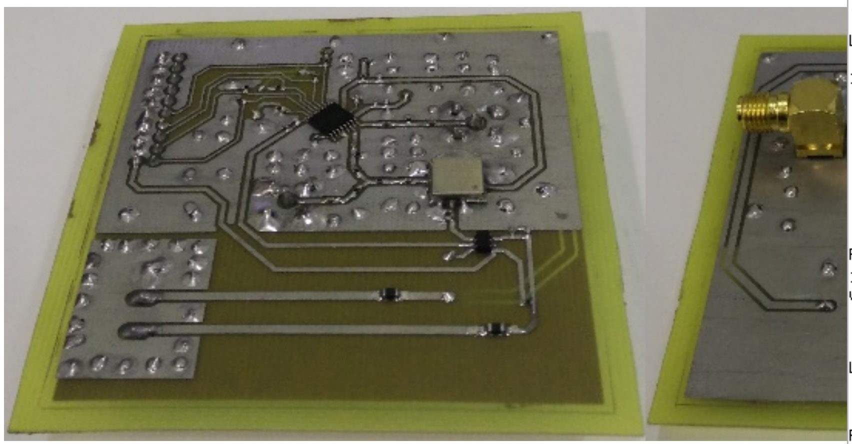
= 30dBm

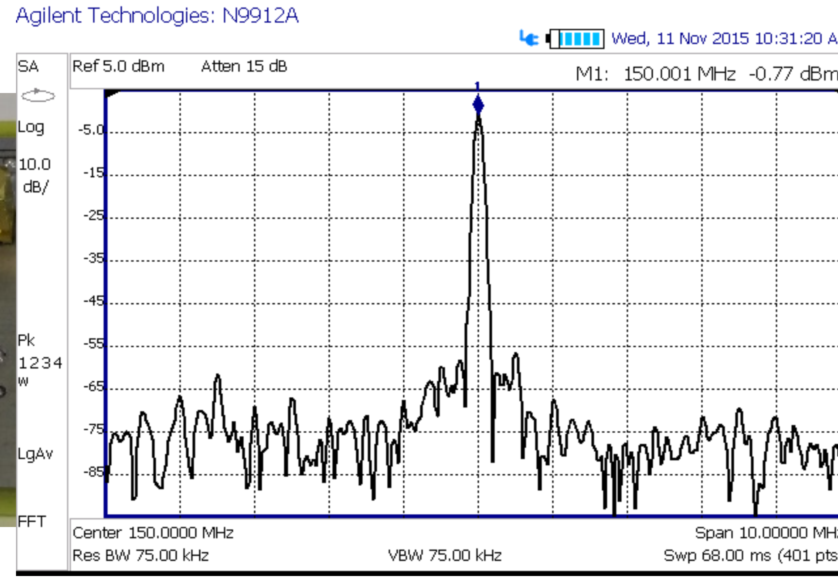
Loss

estimated=

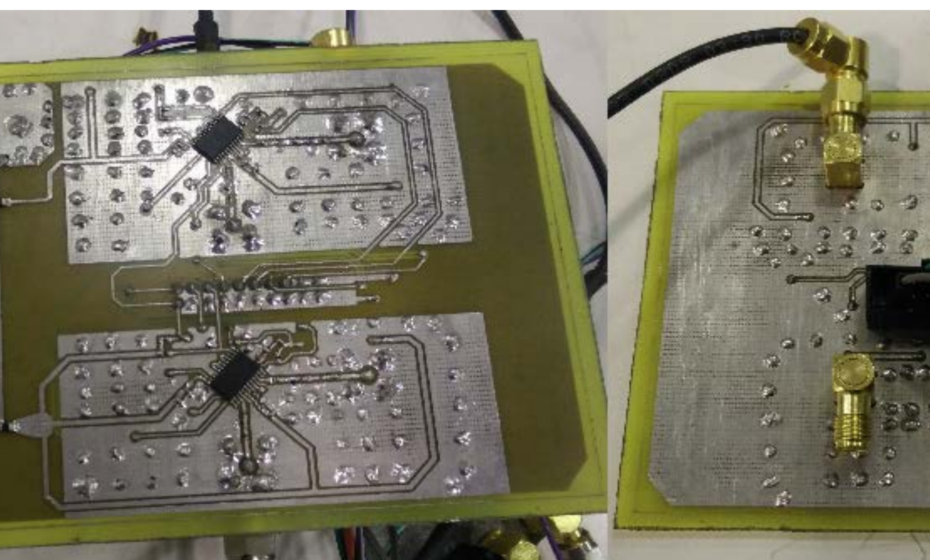
145dB

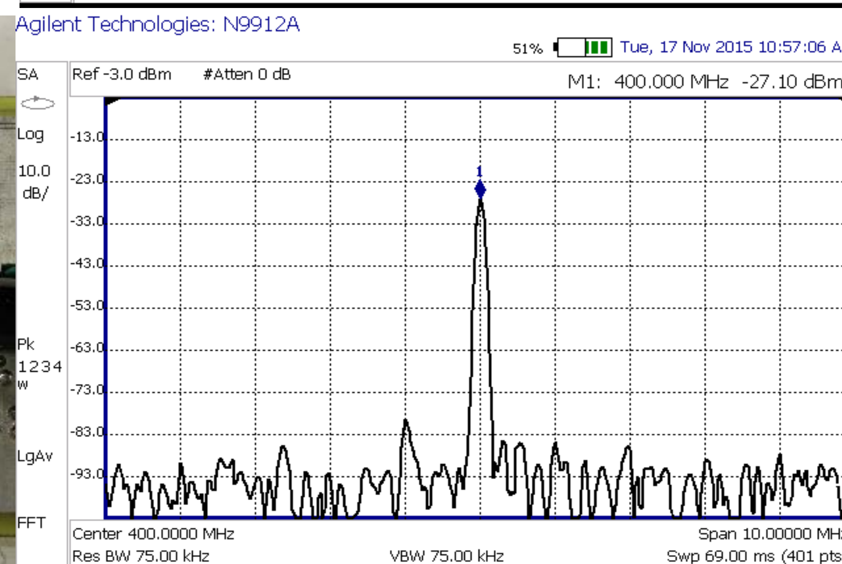
Prototype 1





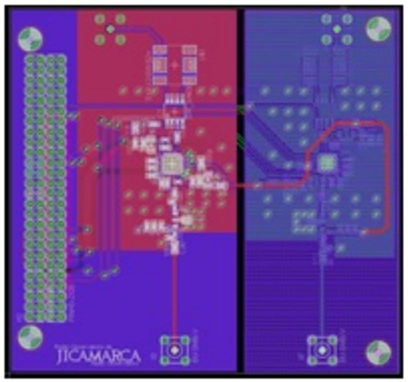
150 MHz

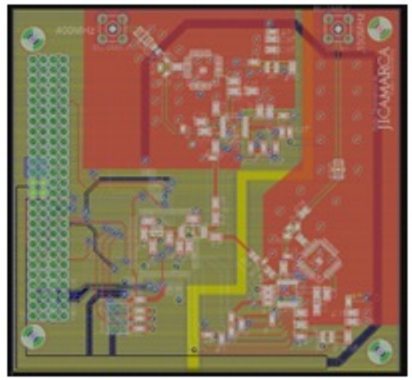




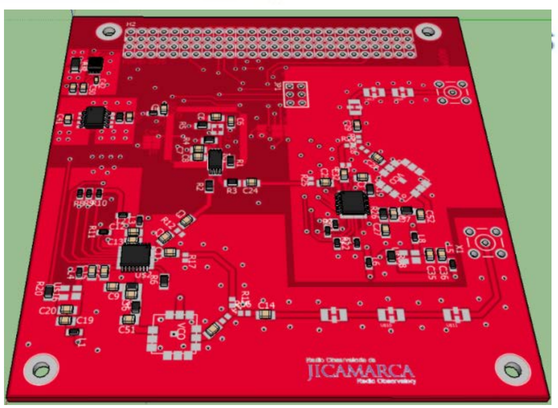
400 MHz

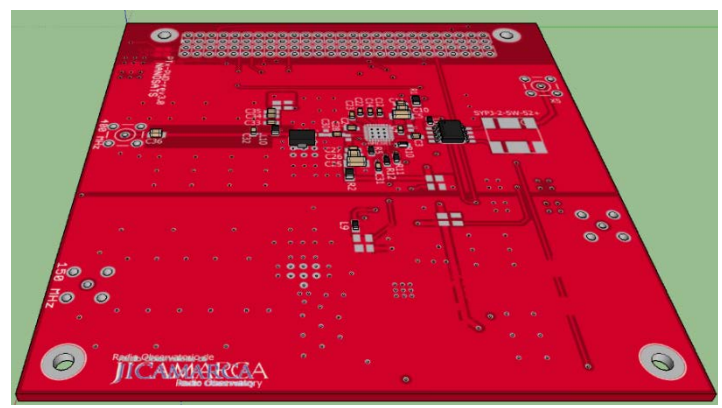
Prototype 2



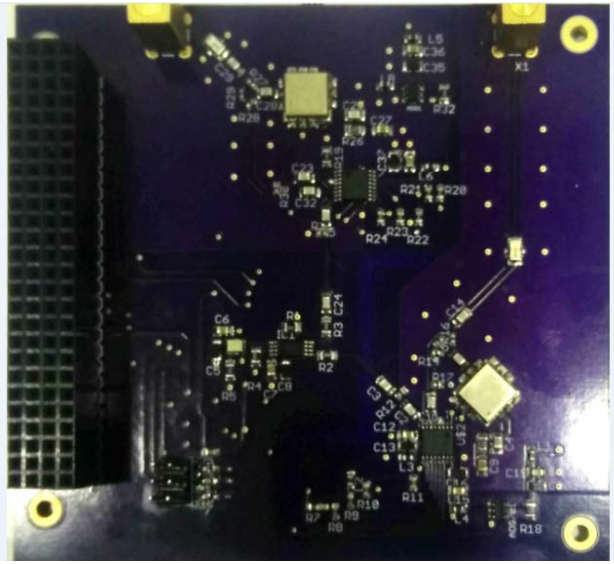


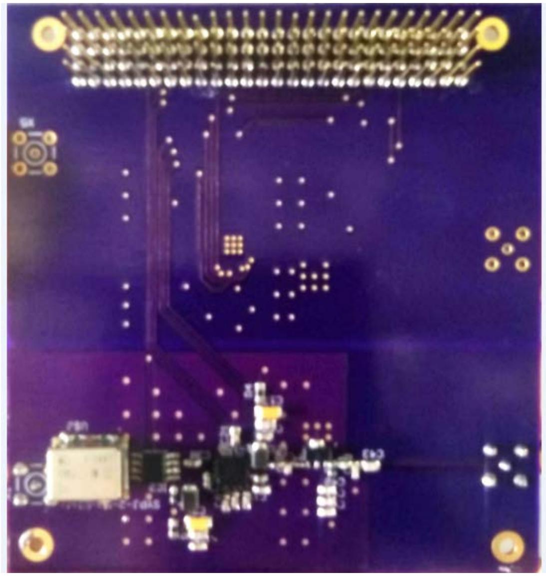
Signal generation
Power boards

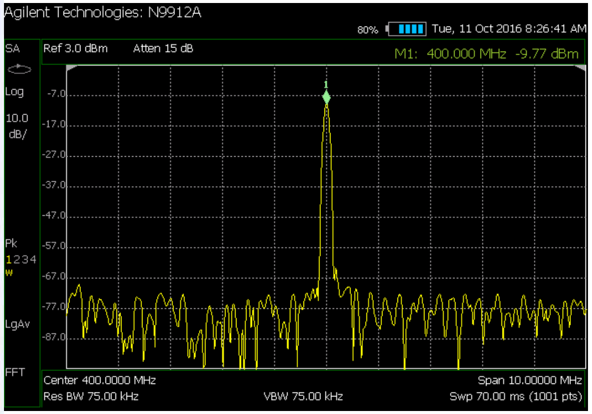




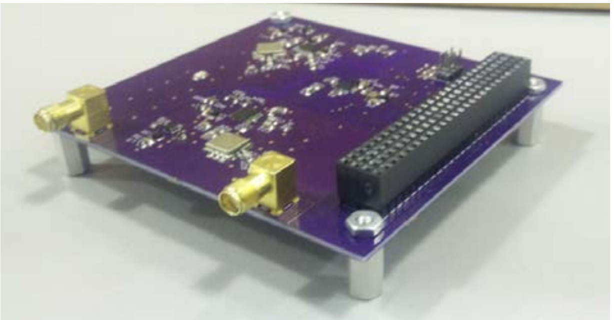
Prototype 2

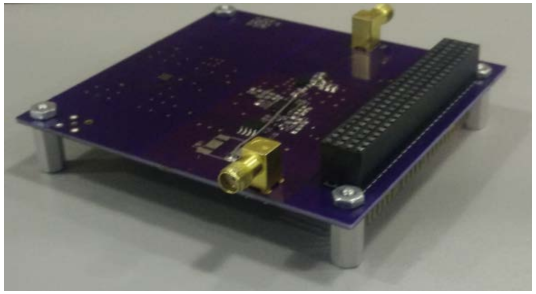


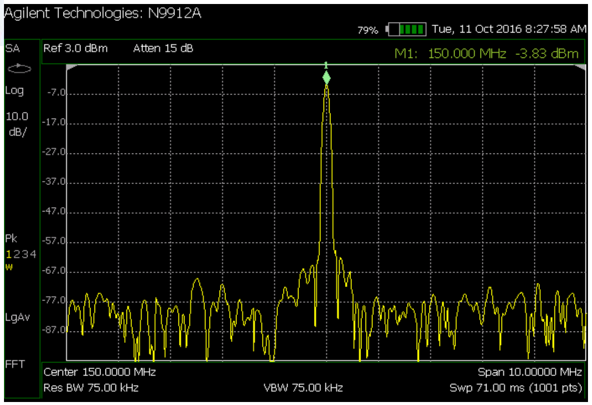




Agilent Technologies: N9912A
80%
Tue, 11 Oct 2016 8:26:41 AM
SA
Ref 3.0 dBm
Atten 15 dB
M1: 400.000 MHz -9.77 dBm
Log
10.0
dB/
Pk
LgAv
FFT
Center 400.0000 MHz
Res BW 75.00 kHz
VBW 75.00 kHz
Span 10.00000 MHz
Swp 70.00 ms (1001 pts)

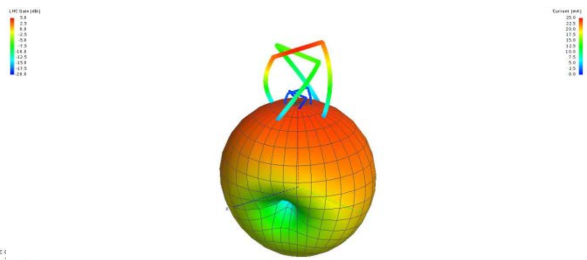


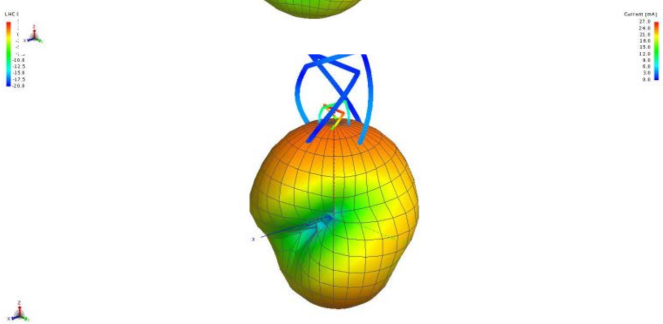


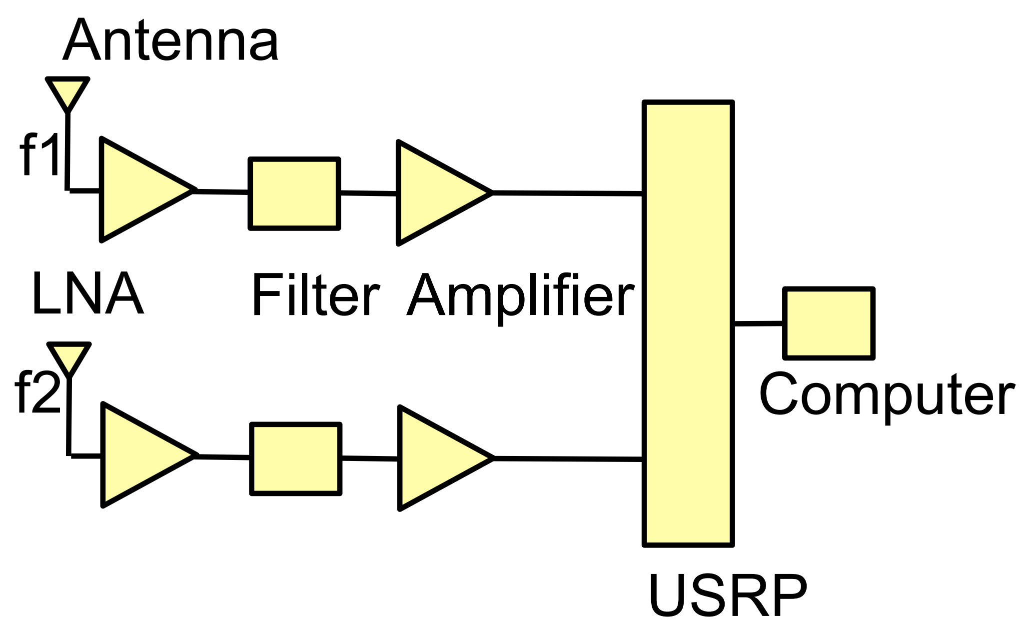


Agilent Technologies: N9912A
79%
Tue, 11 Oct 2016 8:27:58 AM
SA
Ref 3.0 dBm
Atten 15 dB
M1: 150.000 MHz -3.83 dBm
Log
10.0
dB/
Pk
LgAv
FFT
Center 150.0000 MHz
Res BW 75.00 kHz
VBW 75.00 kHz
Span 10.00000 MHz
Swp 71.00 ms (1001 pts)

Receiver Block Diagram



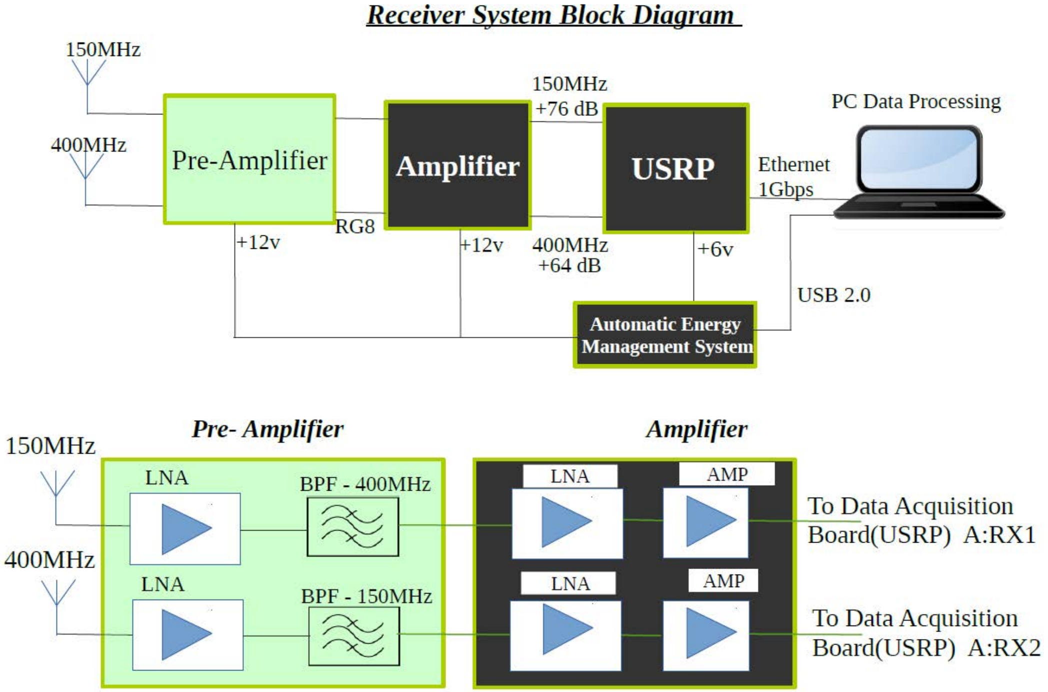




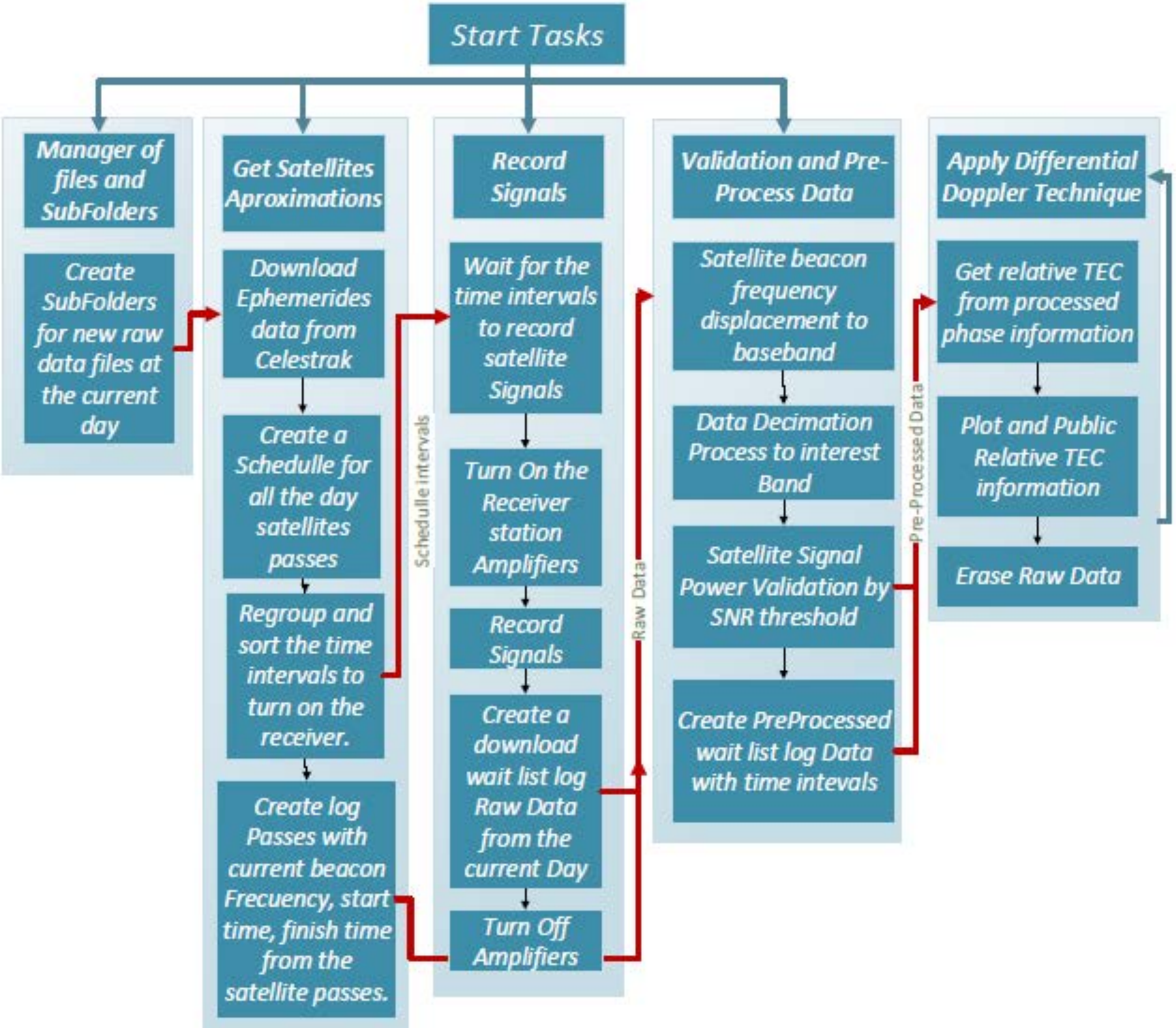
QFH antenna

Receiver Block Diagram

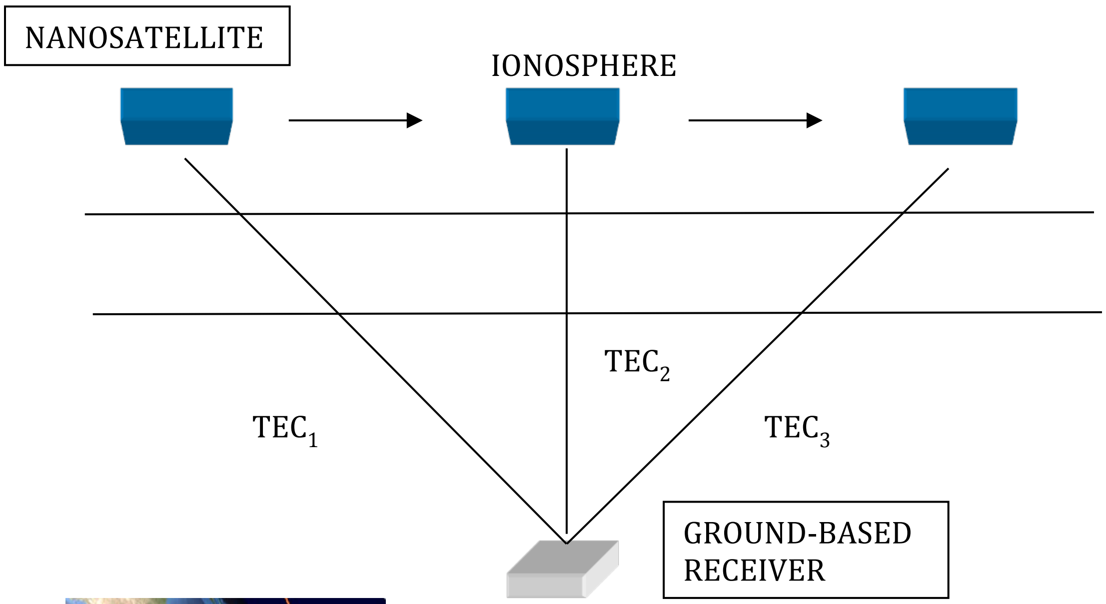
QFH antenna

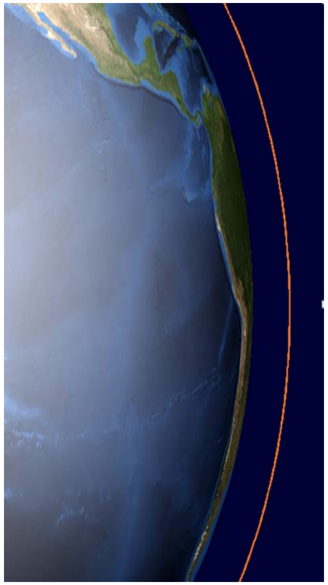


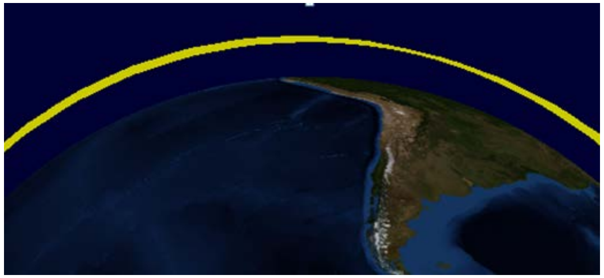
Receiver software algorithm



Proposed mission





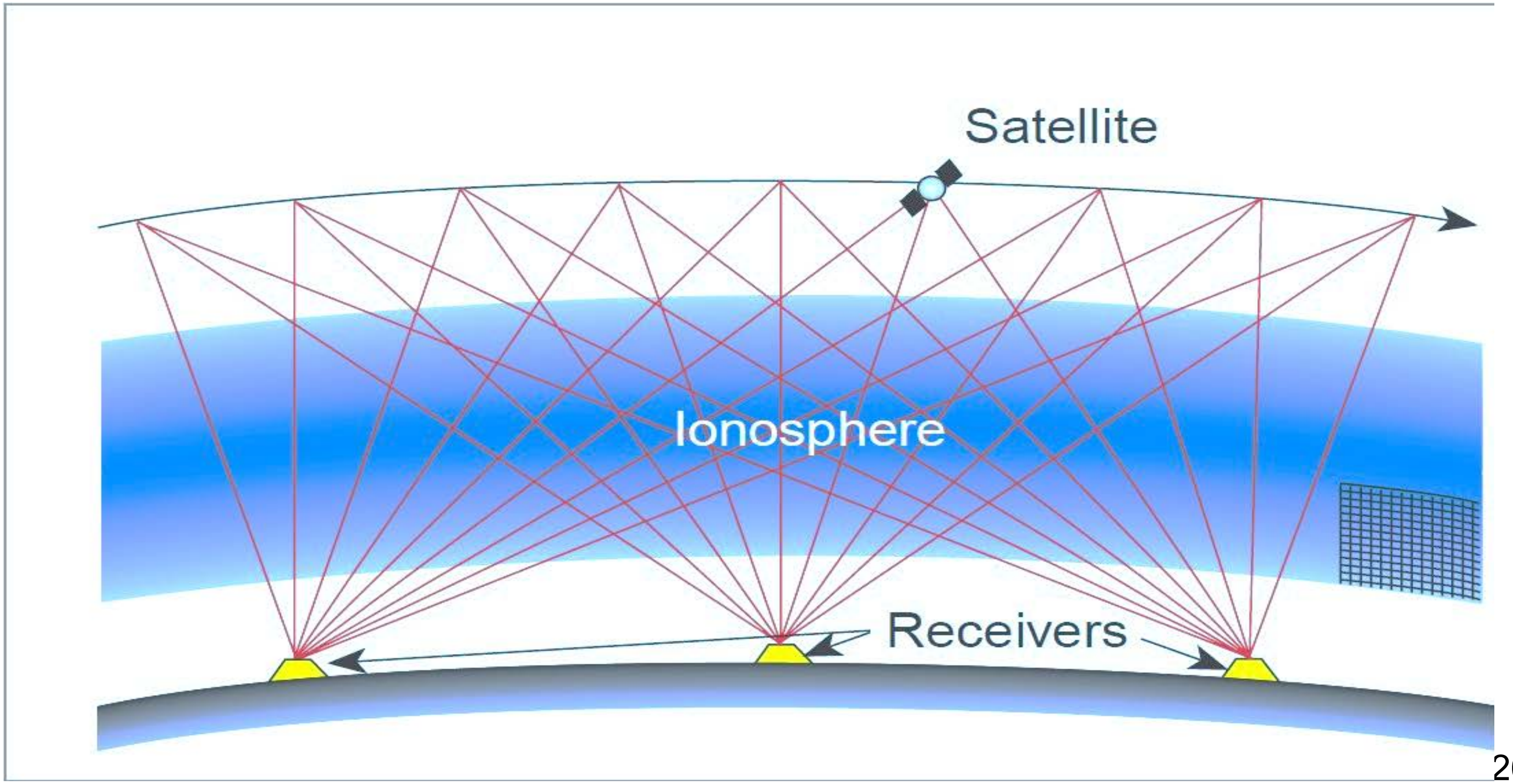


- Nanosatellite orbiting above the ground-base station sending signals at different times to measure TEC along different paths

- Polar (left) and low inclination (right) orbit possibilities for studies of the ionosphere near the Jicamarca Radio Observatory by using nanosatellite radio beacon and a ground-based receiver.

Future work

- Payloads: Nanosatellite and rocket sounding probes
- Increase number of receivers> Tomography



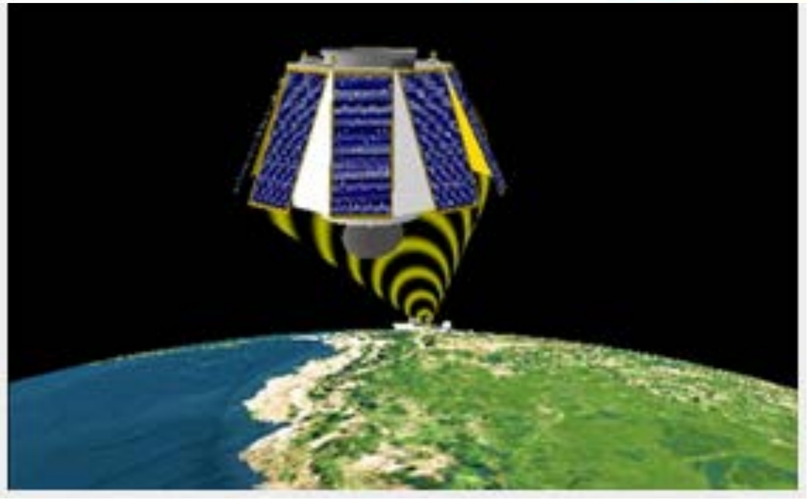
Preliminary measurements at Jicamarca

DMSP F15

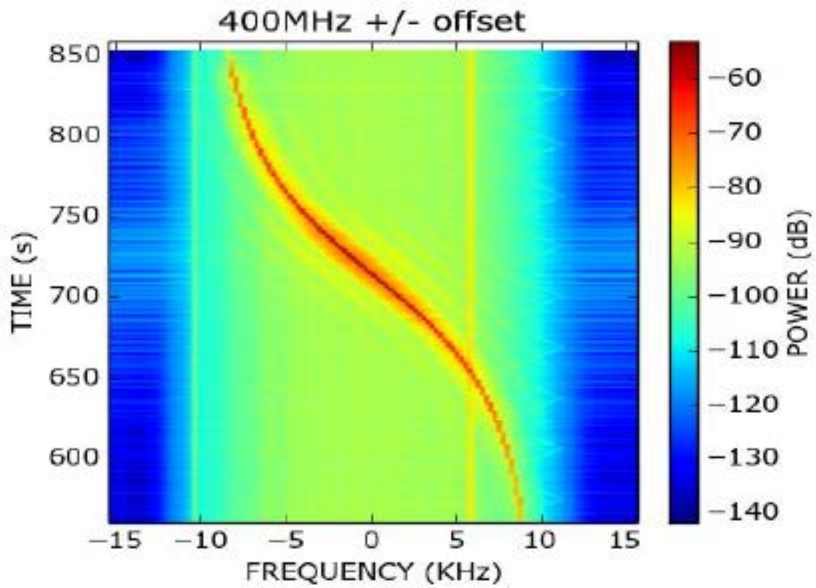
- The DMSP F15 satellite is in a near-circular, sun-synchronous, polar orbit. Temporal Coverage: 24 January 2000 to present
- Maximum altitude: 851km
- Minimum altitude: 837 km
- Inclination: 98.9 degrees
- Period: 101.8 minutes
- 150, 400 MHz

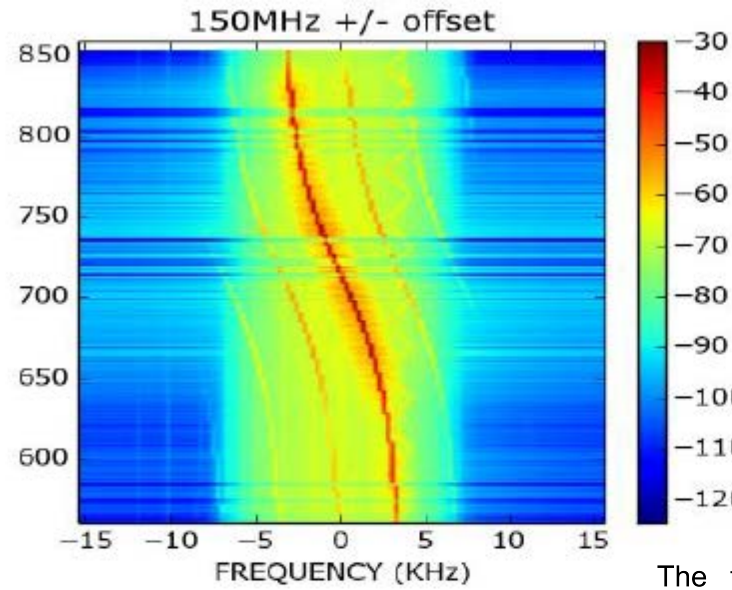
CASSIOPE

- Orbit 325 x 1500 km, 80.99° inclination
- Orbital Period 103 minutes (14 orbits per day)
- e-POP scientific instruments
- Coherent Electromagnetic Radiation tomography experiment (CER)
- 150, 400, 1067 MHz



Preliminary measurements at Jicamarca

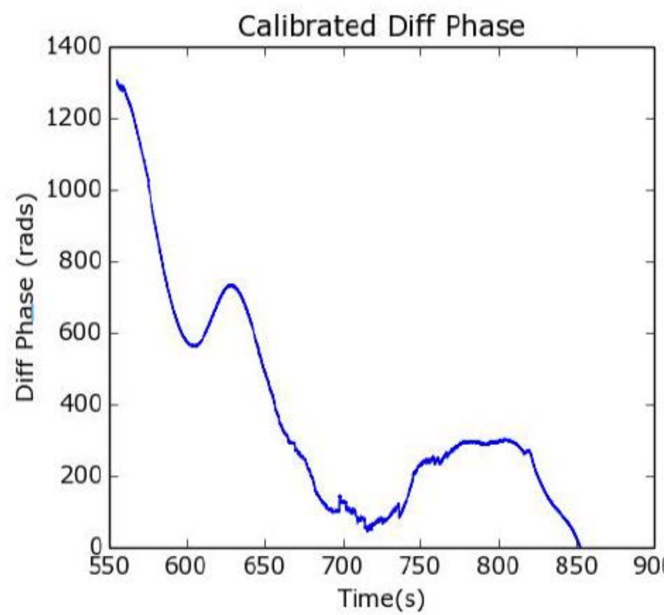




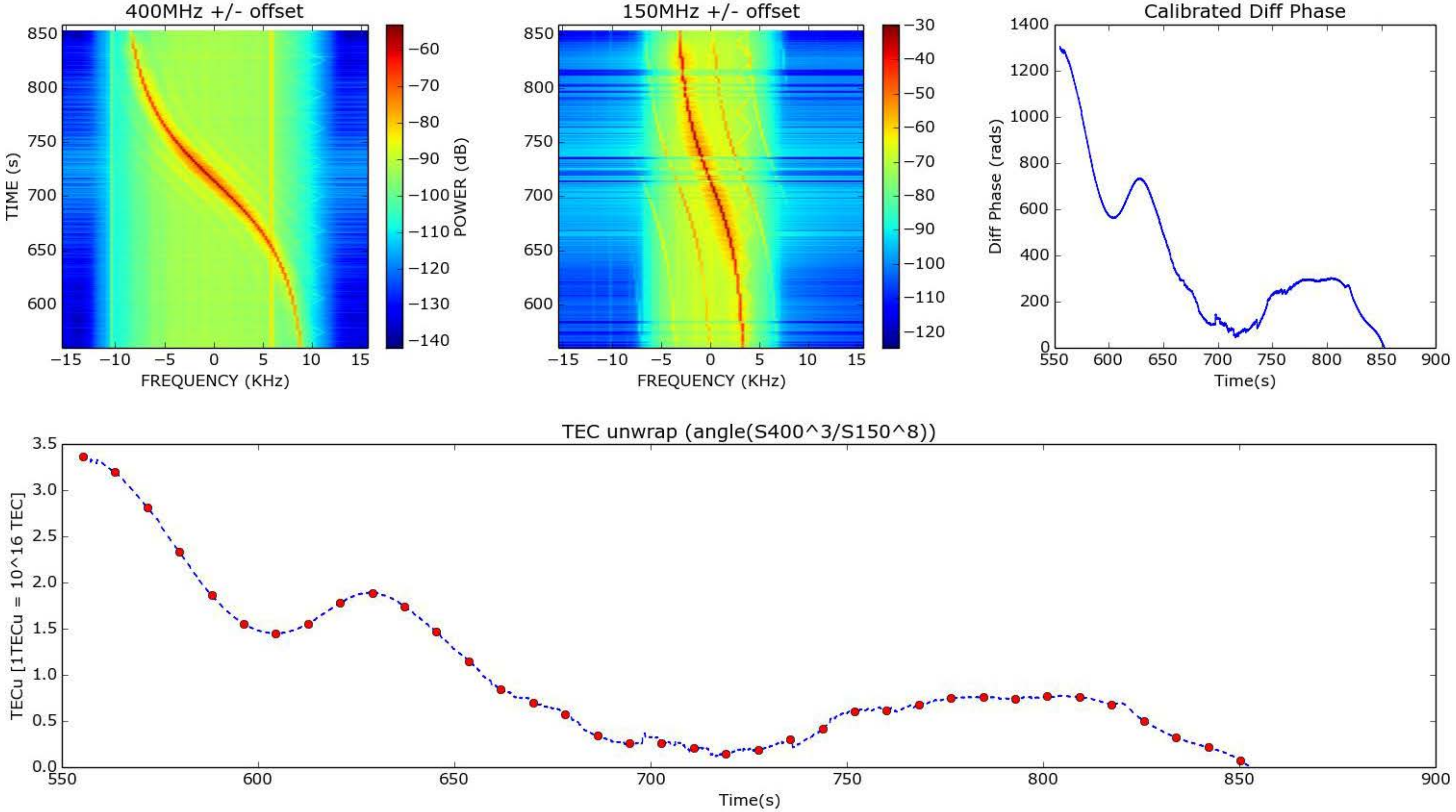
The frequency spectrum obtained by applying FFT to the RF signal is shown.

The Doppler effect is observed in the s-shaped curves.

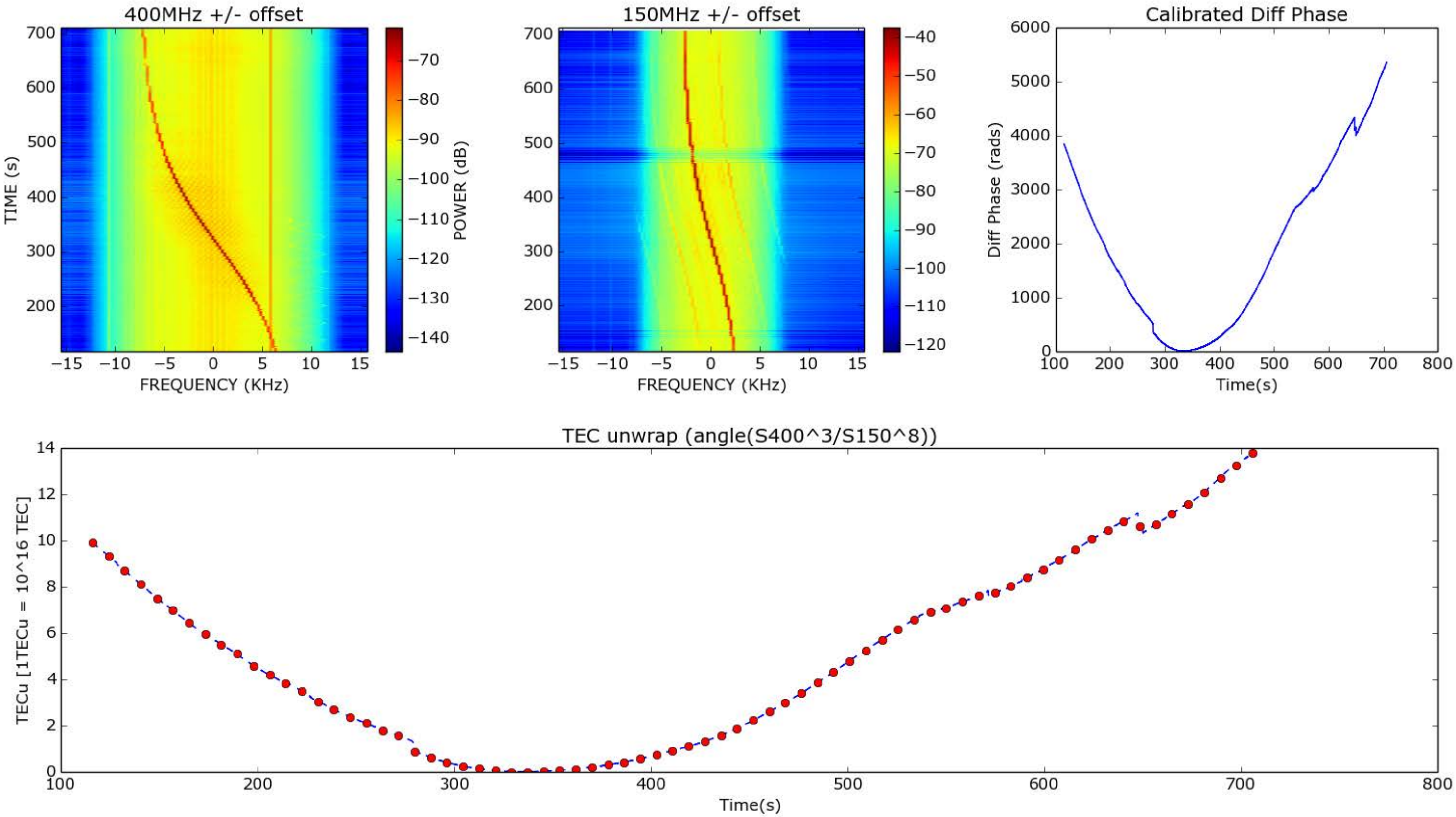
Cassiope Satellite Plot data relative TEC results, from 15th June 2016 1:17UT.



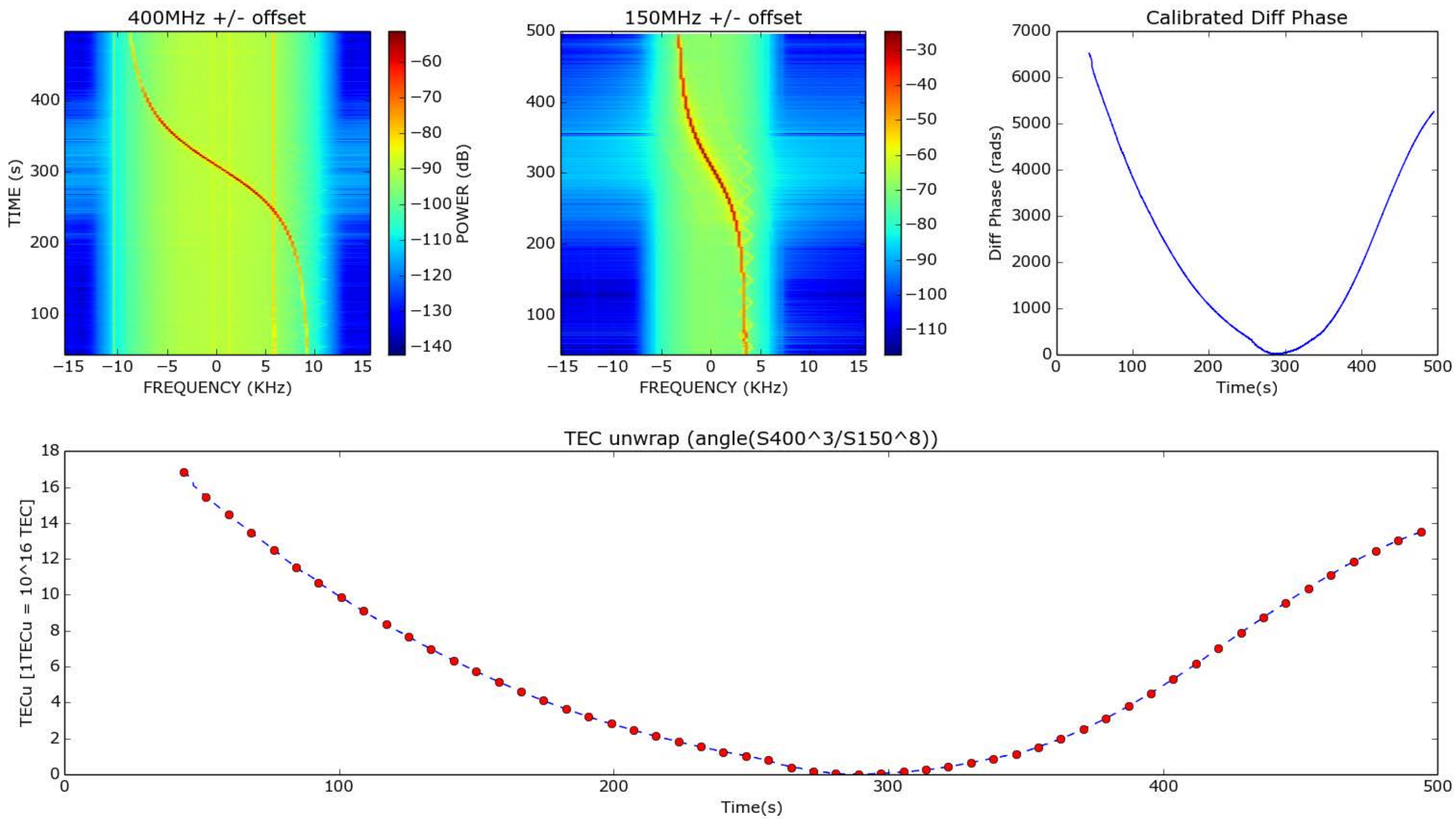
Cassiope Satellite
Plot data relative
TEC results, from
15th June 2016
0117 UT.



Cassiope Satellite
Plot data relative
TEC results, from
15th June 2016
1355 UT.



Cassiope Satellite
Plot data relative
TEC results, from
5 June 2016
0311 UT.

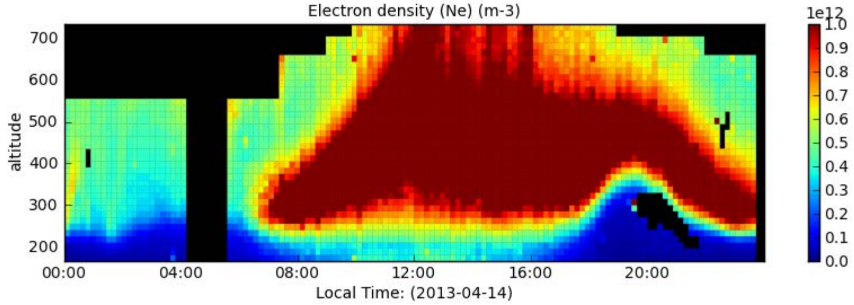


Jicamarca measurements

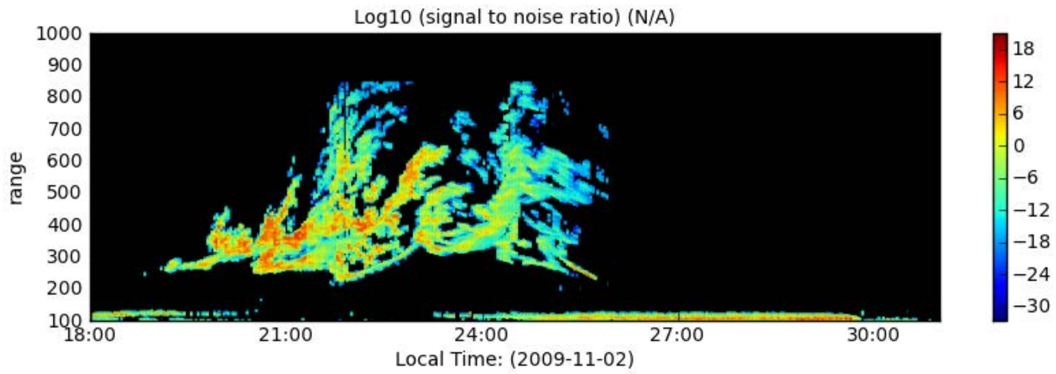
- Combination of radio beacon measurements with:
- Radar measurements
- Density
- Ion drifts
- TEC LISN
- Ionosondes

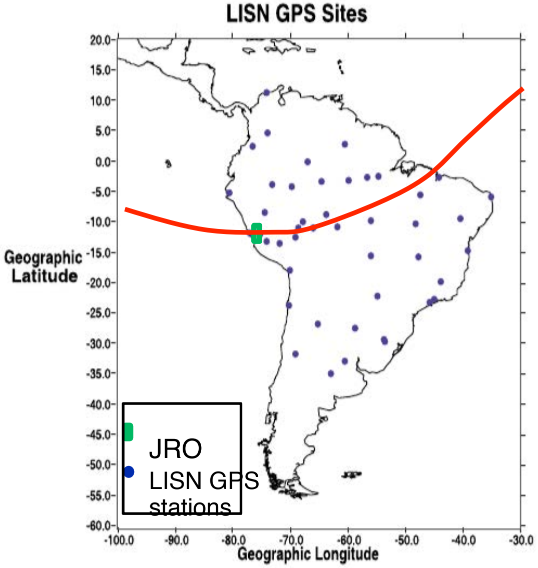
Research

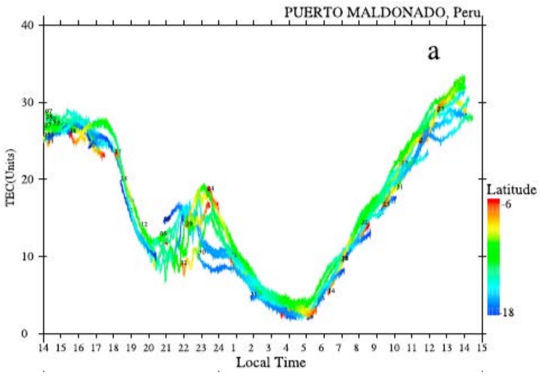
Ne density



Irregularities





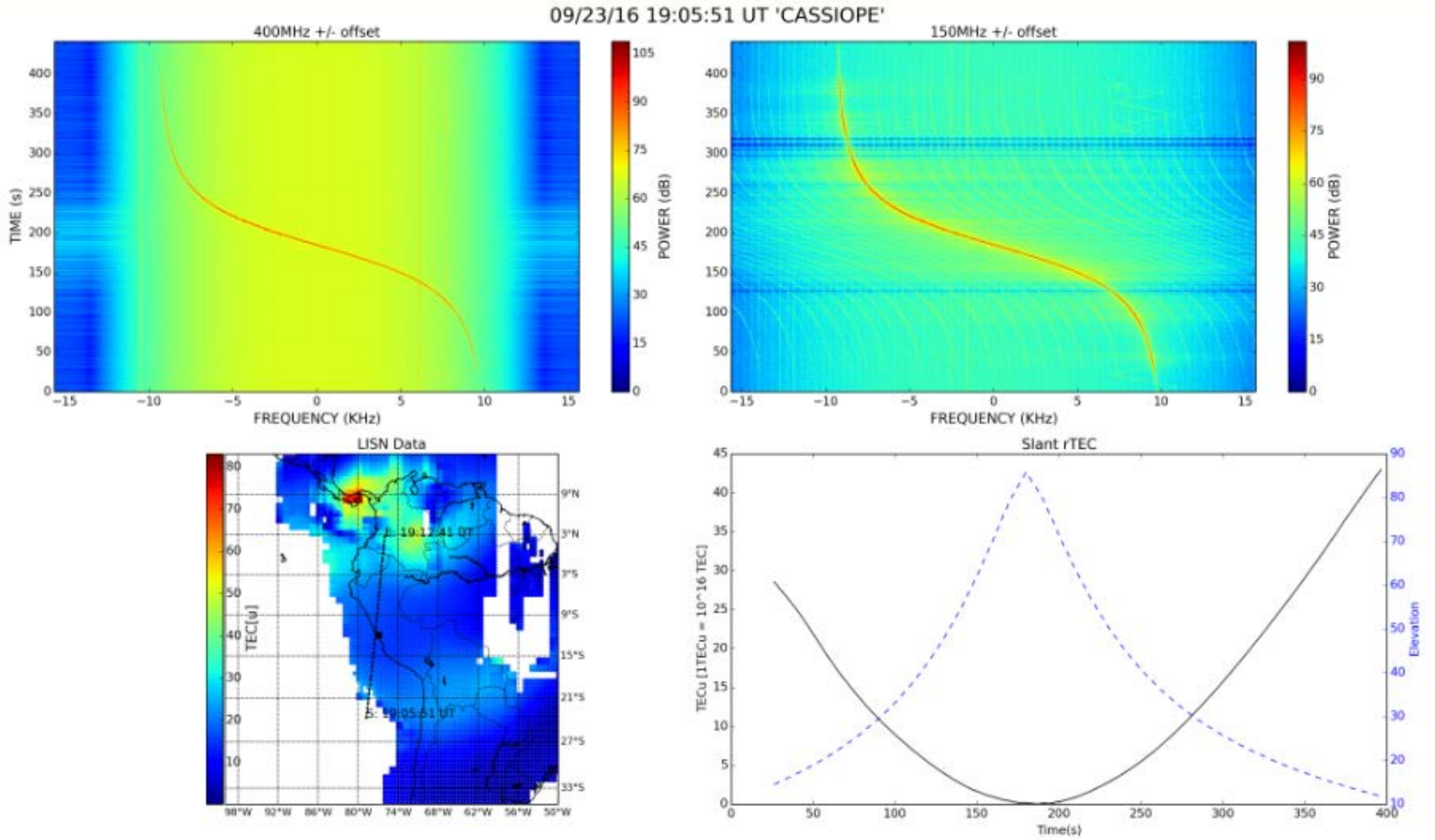


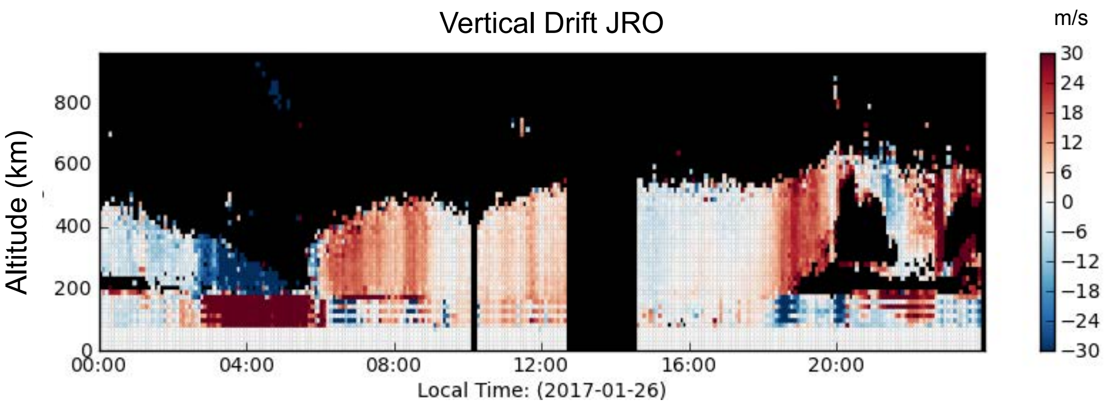
LISN TEC

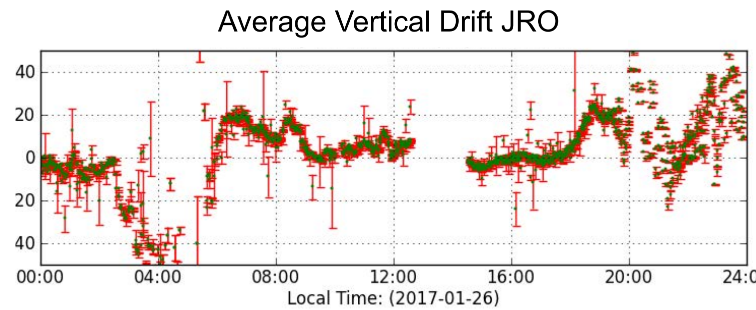
Research Applications

- Investigate ionospheric variability
- TEC mesurements
- Irregularities, spread F
- Longitudinal, latitudinal variations
- Plasma density maps

Preliminary measurements at Jicamarca




Vertical Drift JRO
m/s
Altitude (km)
Local Time: (2017-01-26)
00:00 04:00 08:00 12:00 16:00 20:00
0 200 400 600 800
30 24 18 12 6 0 −6 −12 −18 −24 −30


Average Vertical Drift JRO
Local Time: (2017-01-26)
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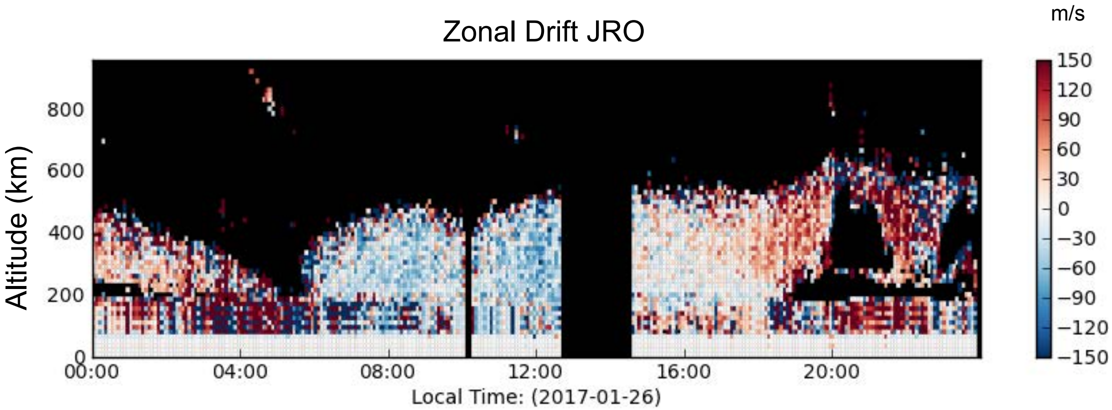
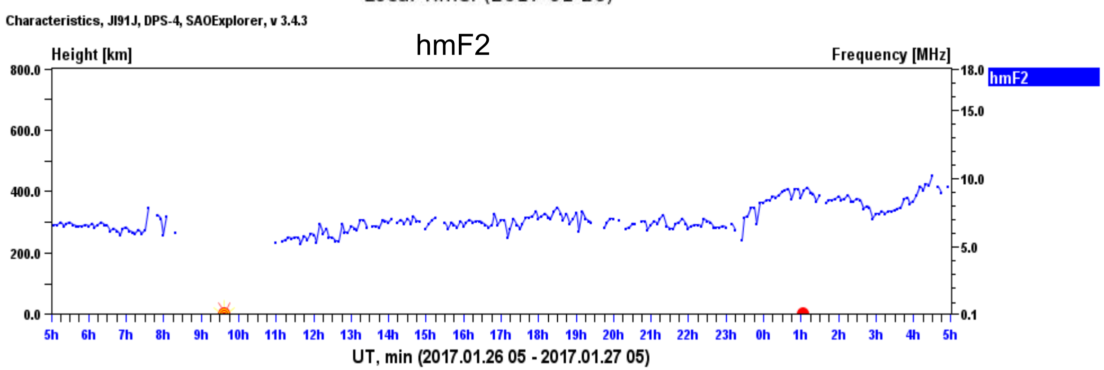
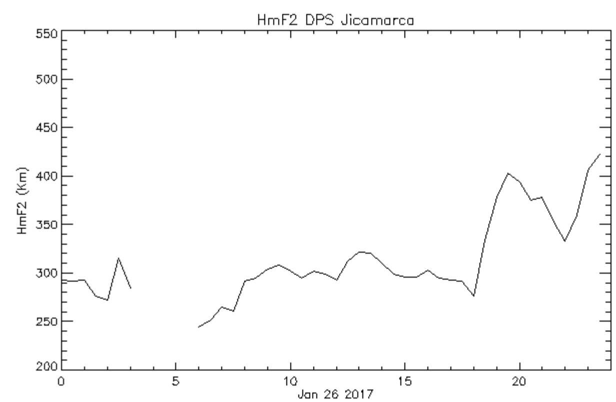
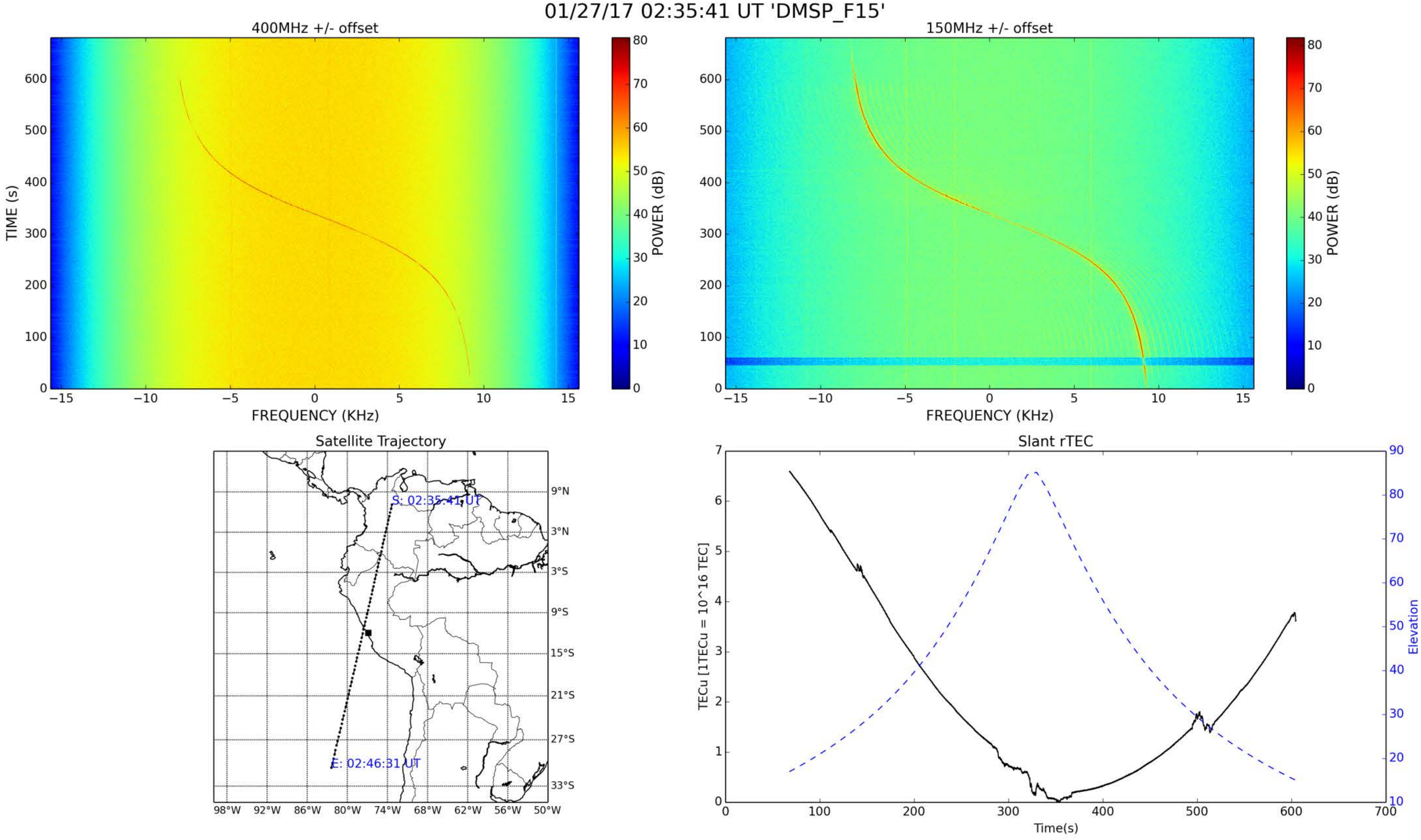
40 20 0 20 40

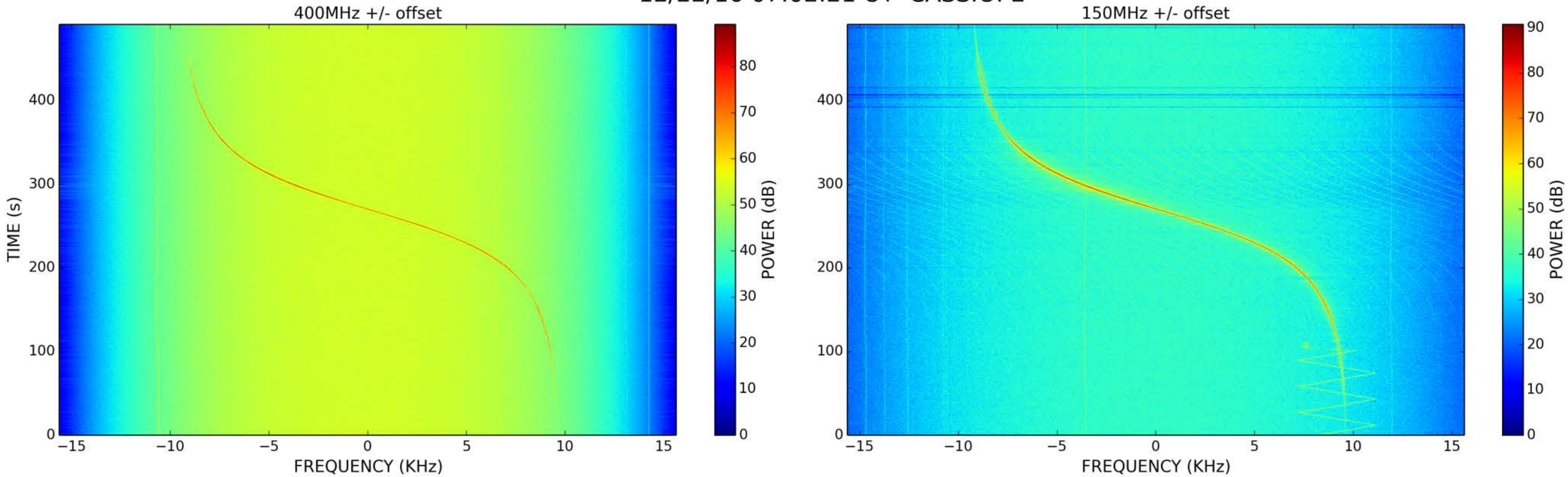

Zonal Drift JRO
m/s
Altitude (km)
Local Time: (2017-01-26)
00:00 04:00 08:00 12:00 16:00 20:00
0 200 400 600 800
150 120 90 60 30 0 −30 −60 −90 −120 −150

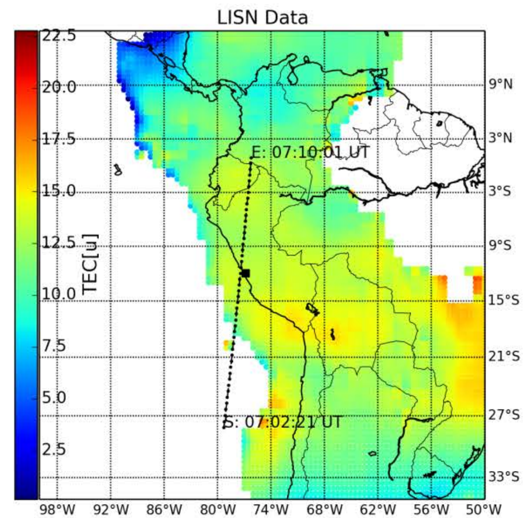

Characteristics, JI91J, DPS-4, SAOExplorer, v 3.4.3
hmF2
Height [km]
Frequency [MHz]
hmF2
0.0 200.0 400.0 600.0 800.0
0.1 5.0 10.0 15.0 18.0
5h 6h 7h 8h 9h 10h 11h 12h 13h 14h 15h 16h 17h 18h 19h 20h 21h 22h 23h 0h 1h 2h 3h 4h 5h
UT, min (2017.01.26 05 - 2017.01.27 05)

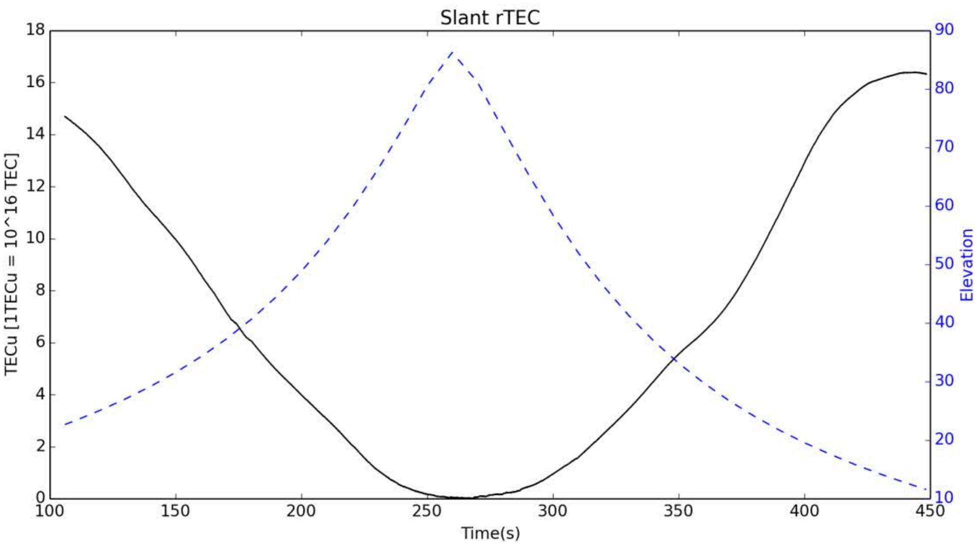

HmF2 DPS Jicamarca
HmF2 (Km)
200 250 300 350 400 450 500 550
0 5 10 15 20
Jan 26 2017

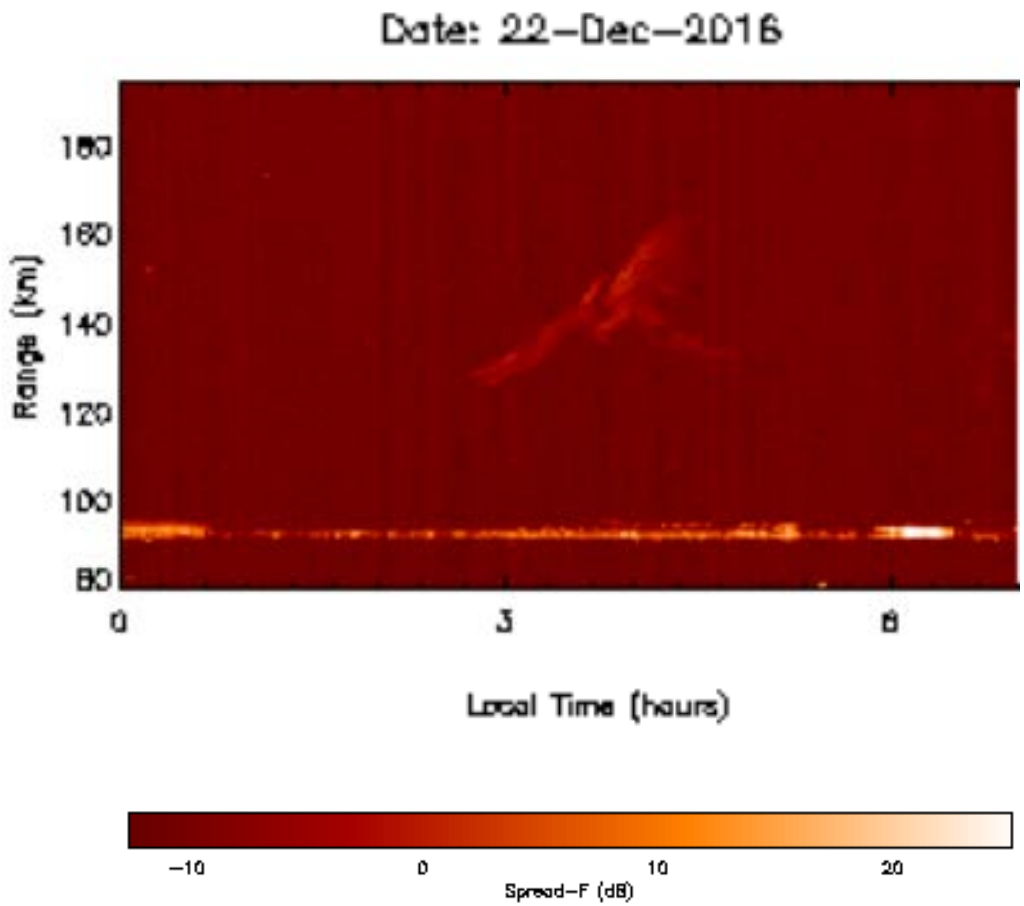

01/27/17 02:35:41 UT 'DMSP_F15'
400MHz +/- offset
150MHz +/- offset
TIME (s)
FREQUENCY (KHz)
POWER (dB)
Satellite Trajectory
S: 02:35:41 UT
E: 02:46:31 UT
Slant rTEC
TECu [1TECu = 10^16 TEC]
Elevation
Time(s)

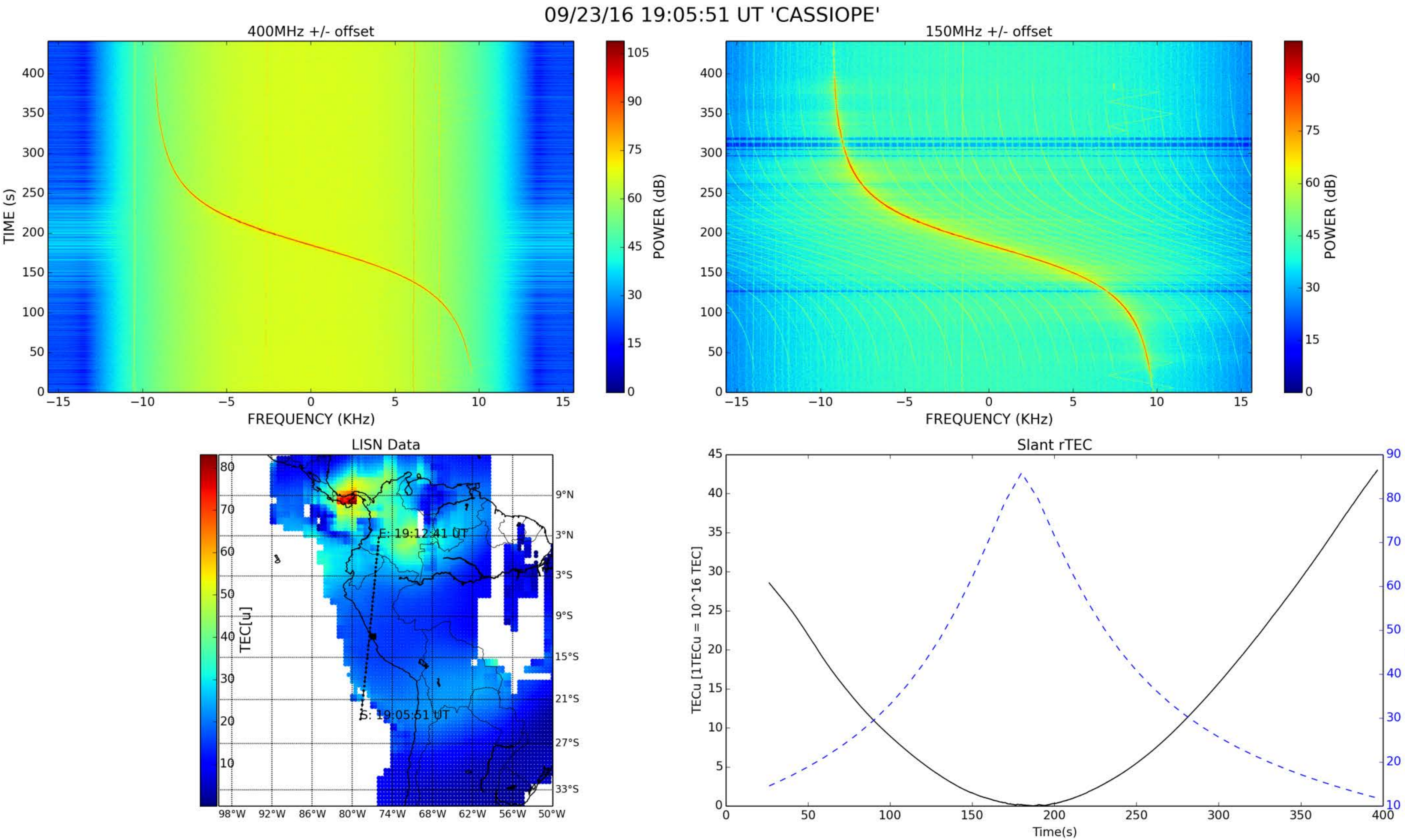
12/22/16 07:02:21 UT 'CASSIOPE'

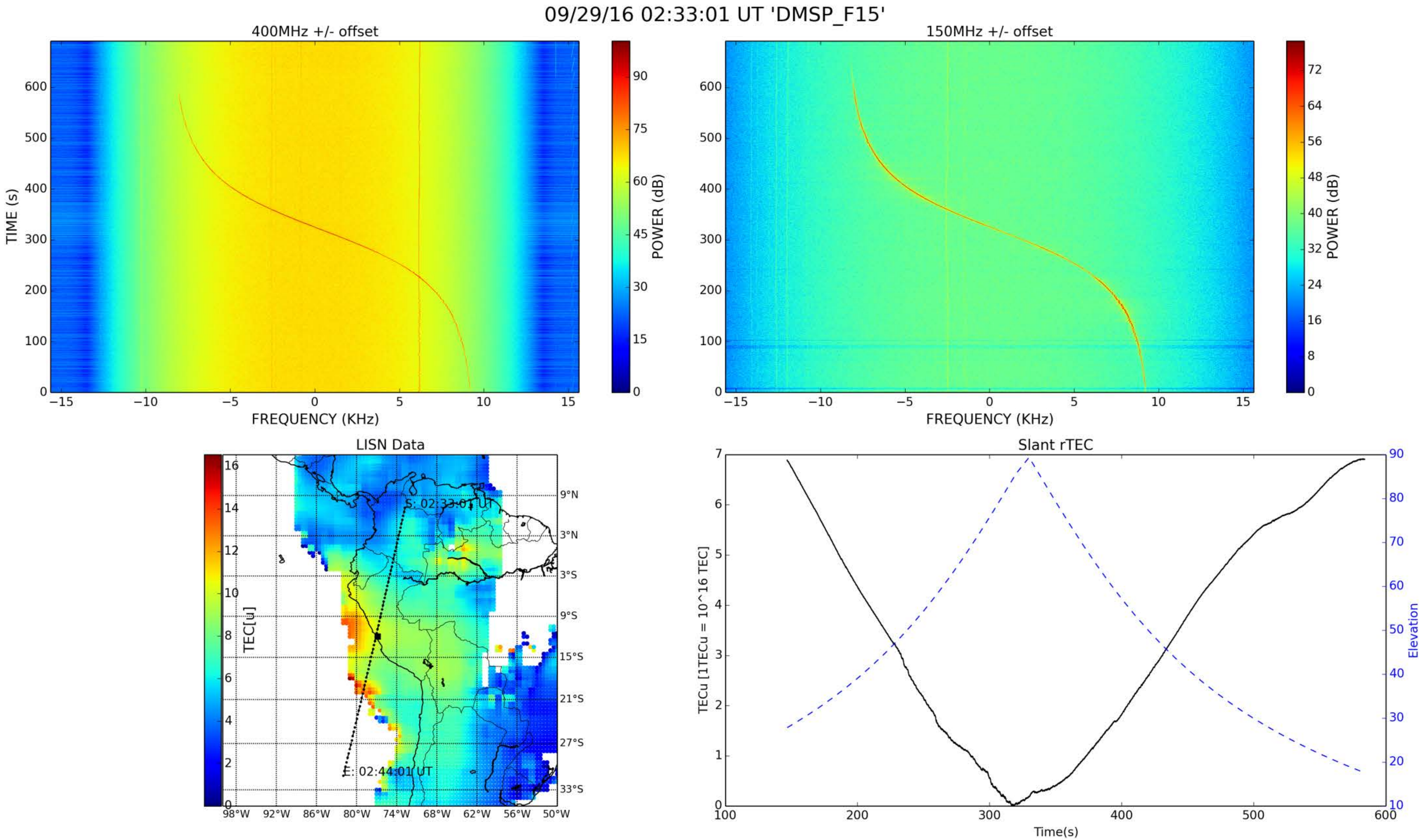




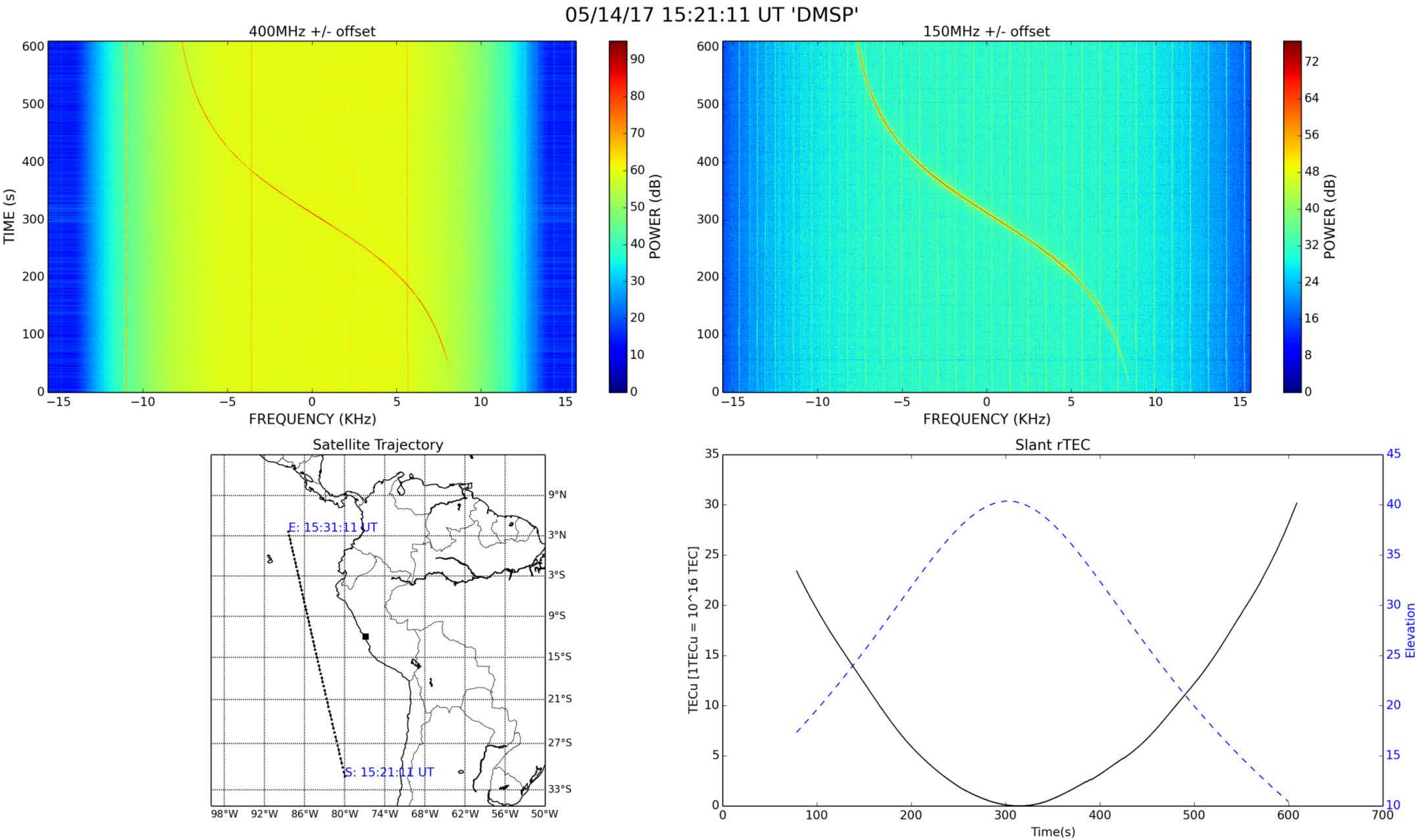


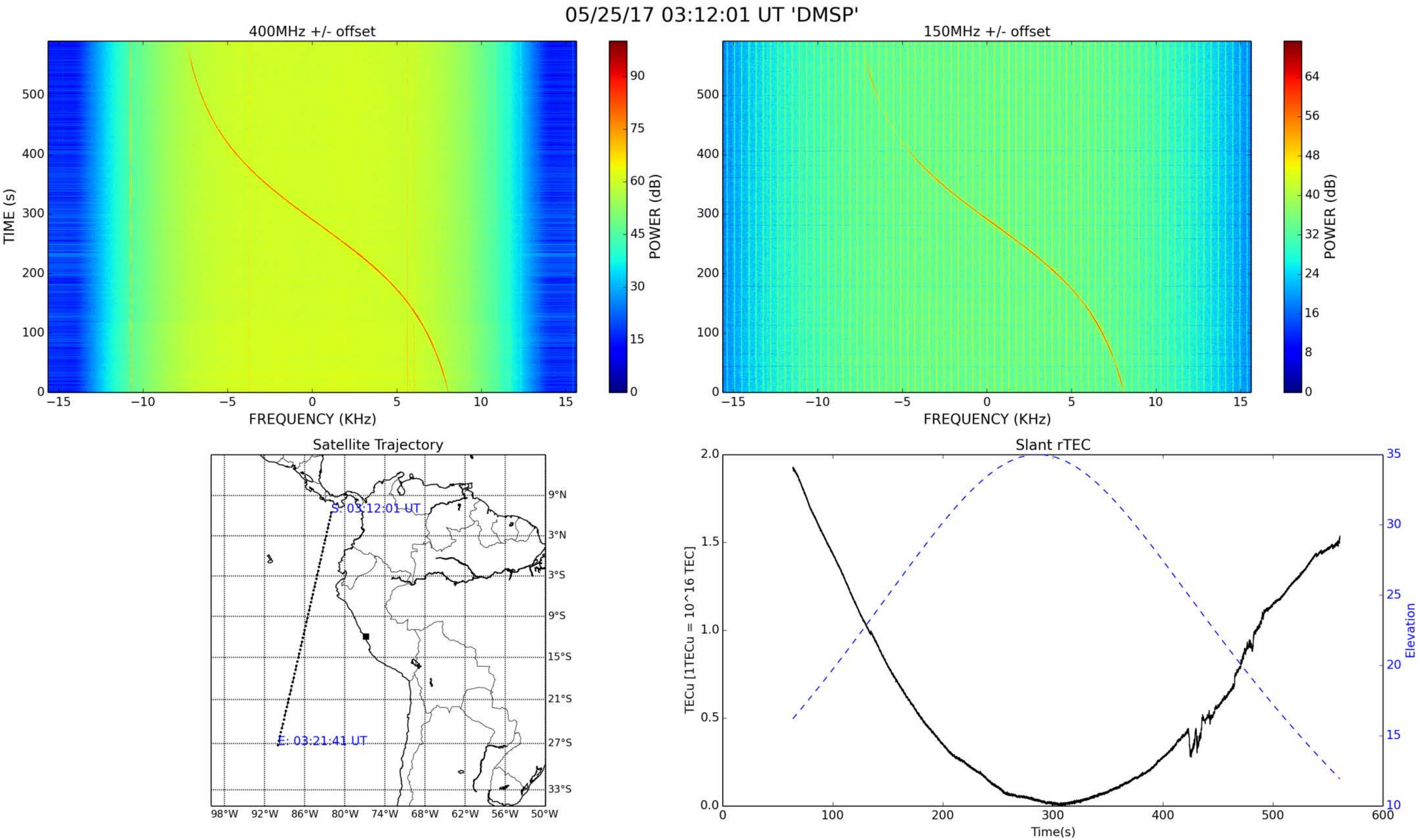

Date: 22-Dec-2016
180
160
140
120
100
80
Range (km)
0
3
6
Local Time (hours)
-10
0
10
20
Spread-F (dB)


09/23/16 19:05:51 UT 'CASSIOPE'
400MHz +/- offset
TIME (s)
FREQUENCY (KHz)
POWER (dB)
150MHz +/- offset
FREQUENCY (KHz)
POWER (dB)
LISN Data
TEC[u]
E: 19:12:41 UT
S: 19:05:51 UT
9°N
3°N
3°S
9°S
15°S
21°S
27°S
33°S
98°W
92°W
86°W
80°W
74°W
68°W
62°W
56°W
50°W
Slant rTEC
TECu [1TECu = 10^16 TEC]
Elevation
Time(s)



09/29/16 02:33:01 UT 'DMSP_F15'
400MHz +/- offset
150MHz +/- offset
TIME (s)
FREQUENCY (KHz)
POWER (dB)
LISN Data
TEC[u]
S: 02:33:01 UT
E: 02:44:01 UT
Slant rTEC
TECu [1TECu = 10^16 TEC]
Elevation
Time(s)


05/14/17 15:21:11 UT 'DMSP'
400MHz +/- offset
150MHz +/- offset
TIME (s)
FREQUENCY (KHz)
POWER (dB)
Satellite Trajectory
E: 15:31:11 UT
S: 15:21:11 UT
9°N
3°N
3°S
9°S
15°S
21°S
27°S
33°S
98°W
92°W
86°W
80°W
74°W
68°W
62°W
56°W
50°W
Slant rTEC
TECu [1TECu = 10^16 TEC]
Elevation
Time(s)


05/25/17 03:12:01 UT 'DMSP'
400MHz +/- offset
TIME (s)
FREQUENCY (KHz)
POWER (dB)
150MHz +/- offset
FREQUENCY (KHz)
POWER (dB)
Satellite Trajectory
S: 03:12:01 UT
E: 03:21:41 UT
9°N
3°N
3°S
9°S
15°S
21°S
27°S
33°S
98°W 92°W 86°W 80°W 74°W 68°W 62°W 56°W 50°W
Slant rTEC
TECu [1TECu = 10^16 TEC]
Time(s)
Elevation

Conclusions

- We are developing a project that consists in the design and implementation of a **ground-based receiver station and a nanosatellite radio beacon transmitter** for ionospheric investigation in the Peruvian sector.
- Total electron content (**TEC**) measurements will be obtained for studying the **variability of the ionosphere** and the occurrence of phenomena such as irregularities.
- The receiver station will be based on software-defined radio equipment and it will be **capable of detecting not only the nanosatellite radio beacon signals but other radio beacons currently in operation** that orbit above the Jicamarca Radio Observatory.
- The TEC measurements will add and **complement the observations** of the already existing ground-based instruments utilized for the investigation of the ionosphere.
- The development is at the implementation stage. We have developed a second prototype for the radio transmitter and ground-based station is in the test process at JRO acquiring signals from DMSP F15 and CASSIOPE..
- Final transmitter version this year and tests.
- **We plan to increase the number of receiver stations in Peru** to enhance the TEC database in the near future.

Acknowledgments

The Instituto Geofísico del Perú gratefully acknowledges the Programa Nacional de Innovación para la Competitividad y Productividad from the Peruvian Ministry of Production for their financial funding support under contract No. 410-PNICP-PIAP-2014 for the project Development of nanosatellite instrumentation and ionospheric measurements and the Pontificia Universidad Católica del Peru for accepting to collaborate with us in our proposed scientific mission.

We also thank The University of Texas at Dallas and Fabiano Rodrigues for their support for our visit and the opportunity to use their equipment for the preliminary tests.

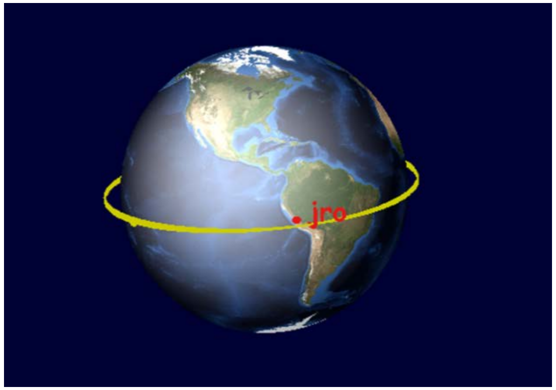
We also thank Jeff Klenzing, Paul Bernhardt, Julio Urbina for their help during our visit to their institutions at the initial phase of the project.

Thank you!

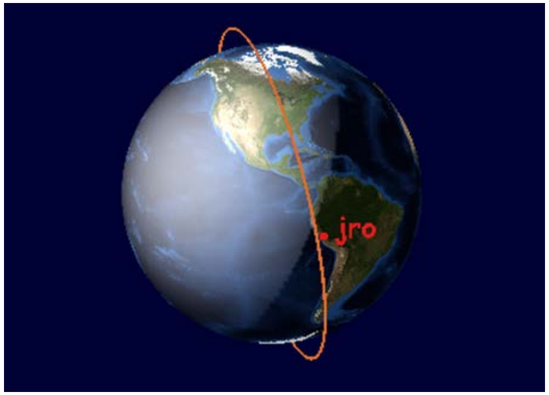
Thank you!

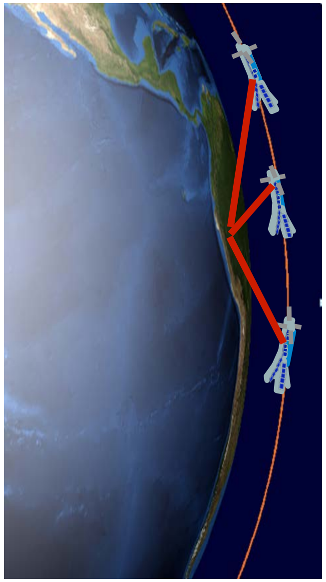
Mission Concept

Low inclination orbit



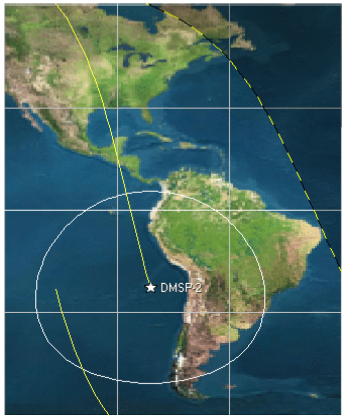
High inclination orbit

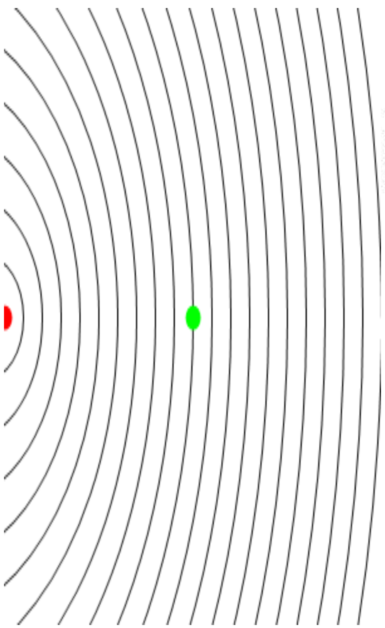


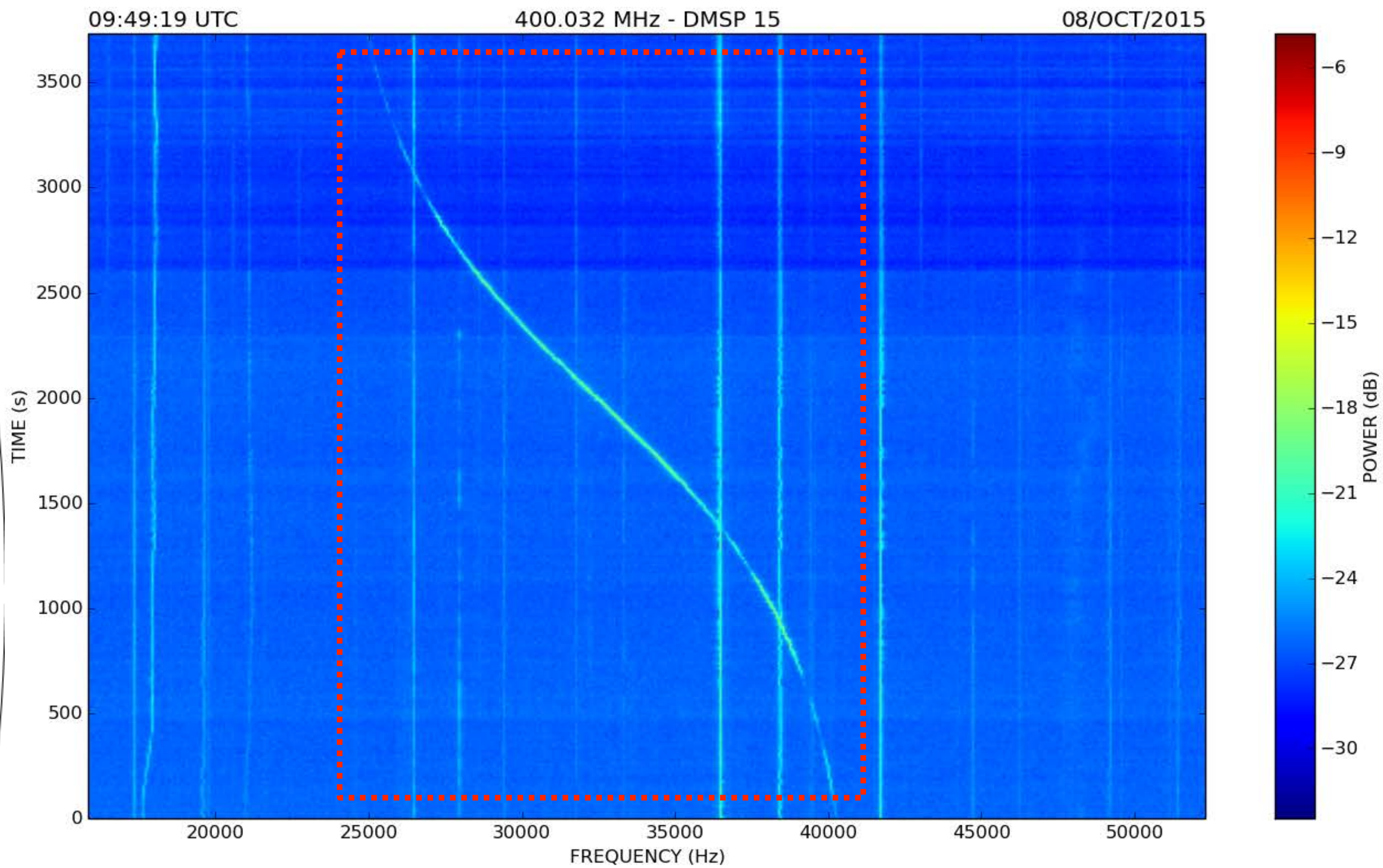


TEC measured at different times

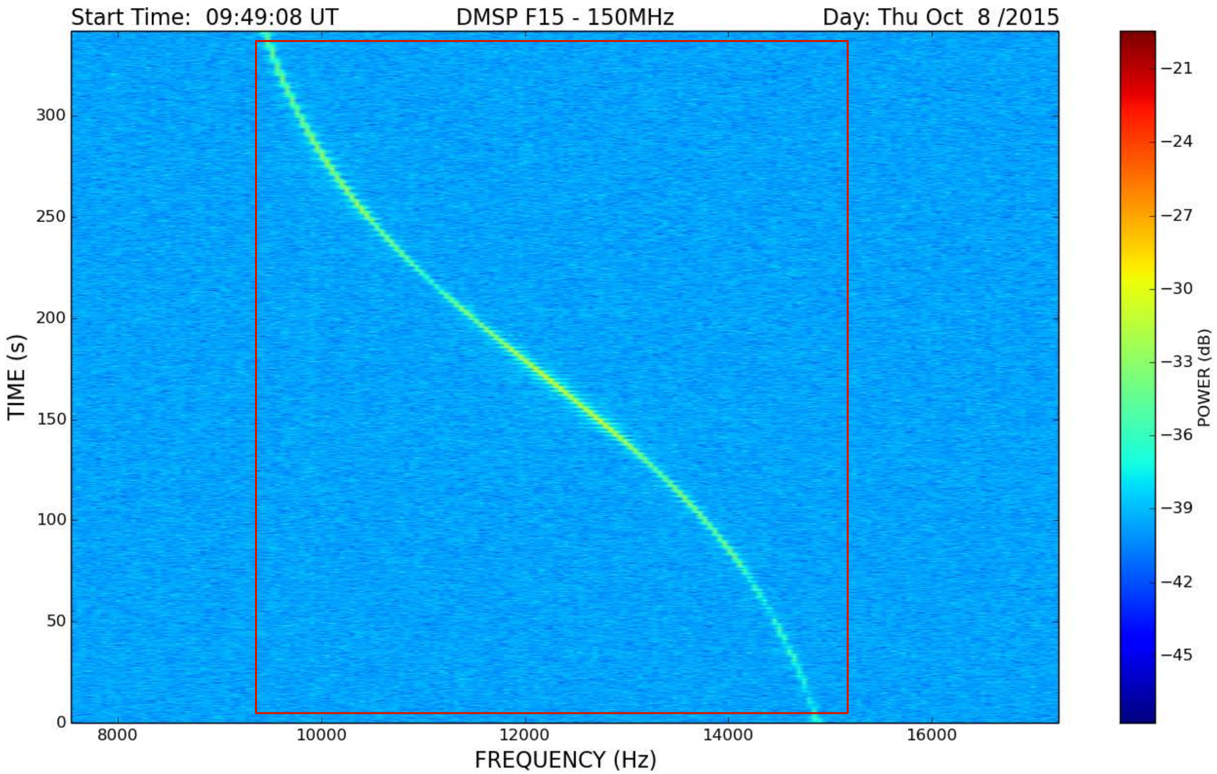
Received satellite signal at 400 MHz





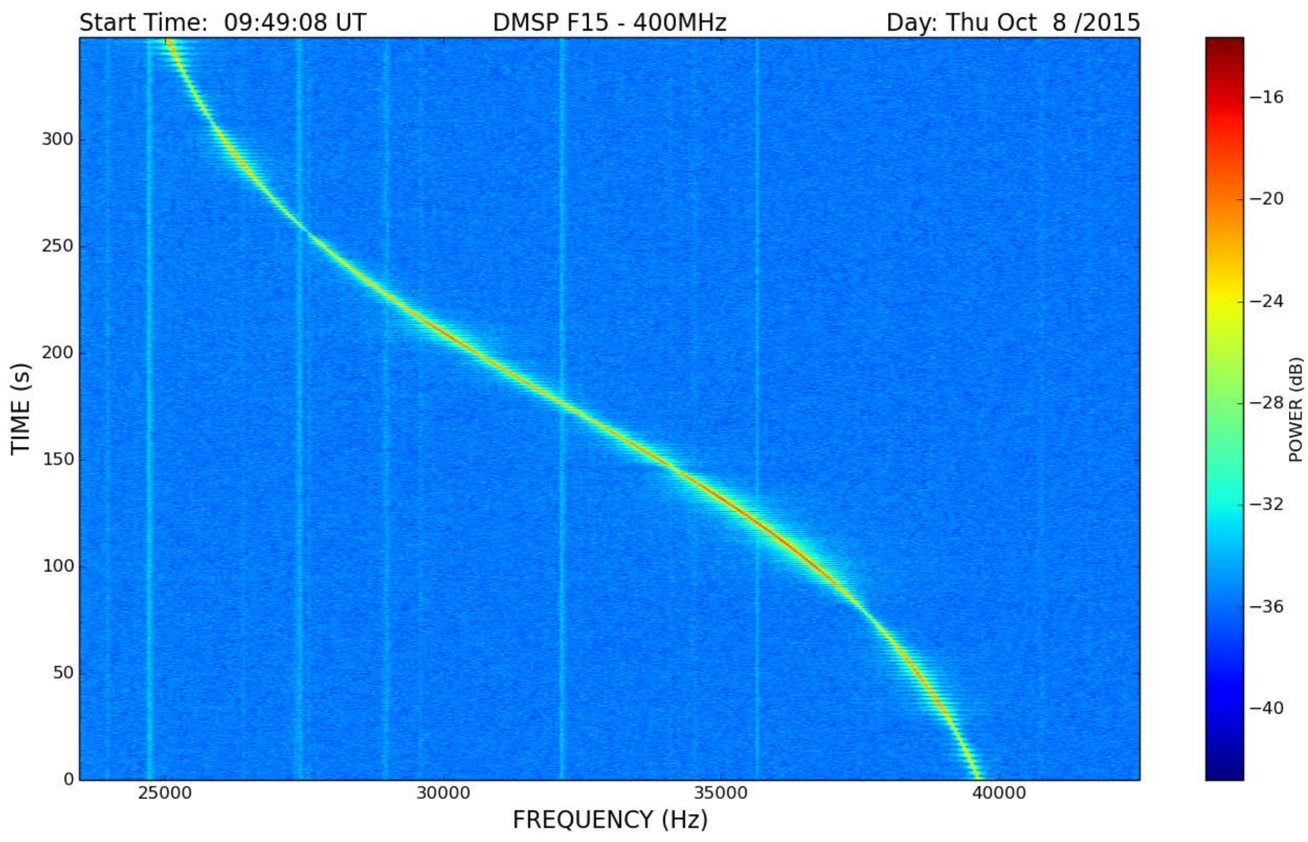


Preliminary measurements



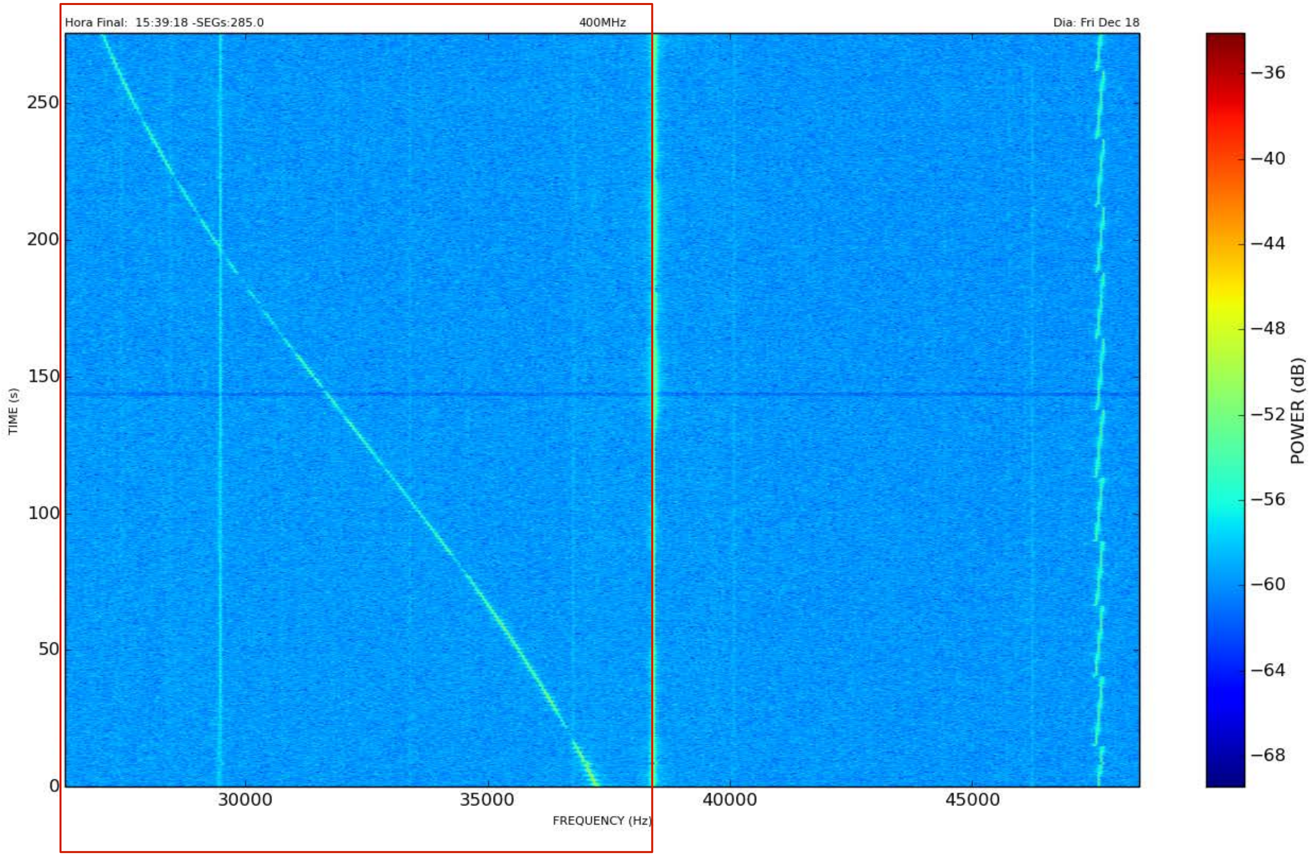
- DMSP when it was orbiting near Dallas, USA.
- The frequency spectrum obtained by applying FFT to the RF signal is shown.
- The Doppler effect is observed in the s-shaped curves.
- The 150 MHz beacon signal with the Doppler effect is observed between 150.009 and 150.015 MHz and the 400 MHz between 400.025 and 400.040 MHz.

Preliminary measurements



- DMSP above Dallas, TX
- 400 MHz between 400.025 and 400.040 MHz.

Preliminary measurements



- Measurements of DMSP radio beacon at 400 MHz above Jicamarca

- DMSP 400 MHz signal with Doppler effect in the frequency spectrum.
- The frequency range is detected between 400.025 and 400. 040 MHz
- December 18 2015 near 1535 LT during this satellite pass.

Modulation