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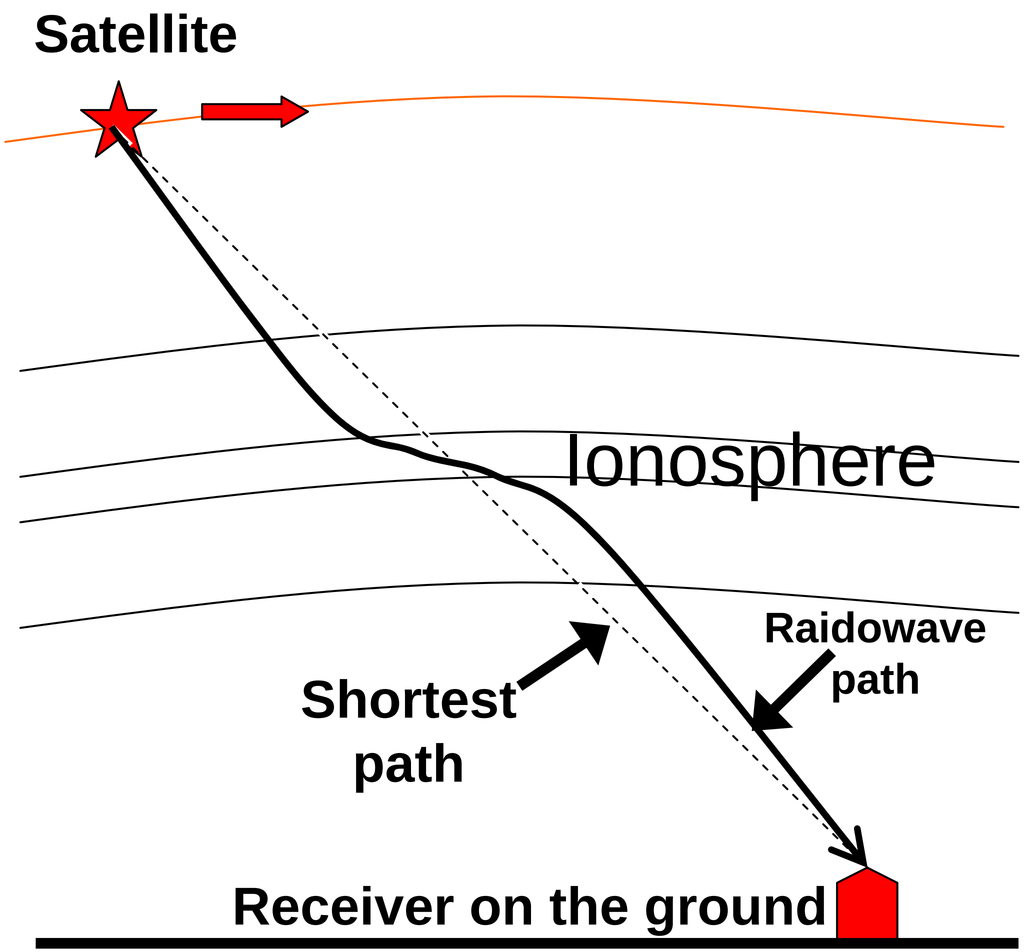
# New development of digital beacon receiver based on GNU Radio

Mamoru Yamamoto
(RISH, Kyoto University)

## Abstract

- We developed a simple digital receiver for satellite-ground beacon experiment.
- The receiver bases on the free hard/software,
  USRP + GNU Radio on LINUX/PC.
- System description, signal processing scheme, and initial results are presented.
- Comparisons with an existing analog receiver and other observations show that the development is very successful.

# Radio beacon experiment of the ionosphere




- VHF(150MHz)/UHF(400MHz) beacon signals are transmitted from satellite, and received on the ground.
- Radiowaves propagate through the Ionosphere that is dissipative media where refractive index is modulated owing to the local plasma density.
- Radiowave ray paths are then bended from the shortest path. The ray paths vary at different wave frequency.
- From close analysis of phase difference between two signals, we can estimate total electron content (TEC) between the satellite and the receiver.

# Beacon experiment basic (1)

Radiowave propagates in plasma with refractive index *n*

$$u = U\cos\left\{2\pi f\left(\frac{x}{C_p} - t\right)\right\} = U\cos\left\{2\pi f\left(\frac{nx}{C} - t\right)\right\}$$

*where, U*: amplitude, *f*: frequency, *c*: speed of light,
$c_p$: phase velocity, *x*: position, *t*: time. Refractive index is a function of *f* and plasma density *N* as,

$$n = \frac{C}{C_p} = 1 - \frac{A}{2f^2}N, \quad \text{constant } A = \frac{(2\pi e)^2}{m\varepsilon_0} = 80.6\mathrm{m}^3/\mathrm{s}^2$$

Total phase $\psi$ at travel length *L* is described as follows.
Here, $\int N\mathrm{d}s$ is the total electron content (TEC).

$$\psi = \frac{2\pi f}{c}L - \frac{\pi A}{Cf}\int N\mathrm{d}s$$

# Beacon experiment basic (2)

We eliminate $L$ by using two radiowaves at $f_1 = pf_r$ and $f_2 = qf_r$. Normally, we select $f_r$ = 50 MHz, $p$=3, and $q$=8, i.e., $f_1$ = 150MHz and $f_2$ = 400MHz. Here phase at both frequency is $\psi_1$ and, $\psi_2$, and the phase difference is,

$$\Phi = \frac{\psi_1}{p} - \frac{\psi_2}{q} = \frac{\pi A}{f_r C}\left(\frac{1}{q^2} - \frac{1}{p^2}\right)\int N\mathrm{d}s$$

Evaluation of phase

Time derivative of $\psi_1$ and $\psi_2$ are Doppler shift $f_{\mathrm{d1}}$ and $f_{\mathrm{d2}}$. We can rewrite this as follows.

$$\frac{f_{d1}}{p} - \frac{f_{d2}}{q} = \frac{\pi A}{f_r C}\left(\frac{1}{q^2} - \frac{1}{p^2}\right)\frac{\mathrm{d}}{\mathrm{d}t}\int N\mathrm{d}s$$

Evaluation of frequency

This is typical “differential Doppler” at 50 MHz.

# Typical analog receiver

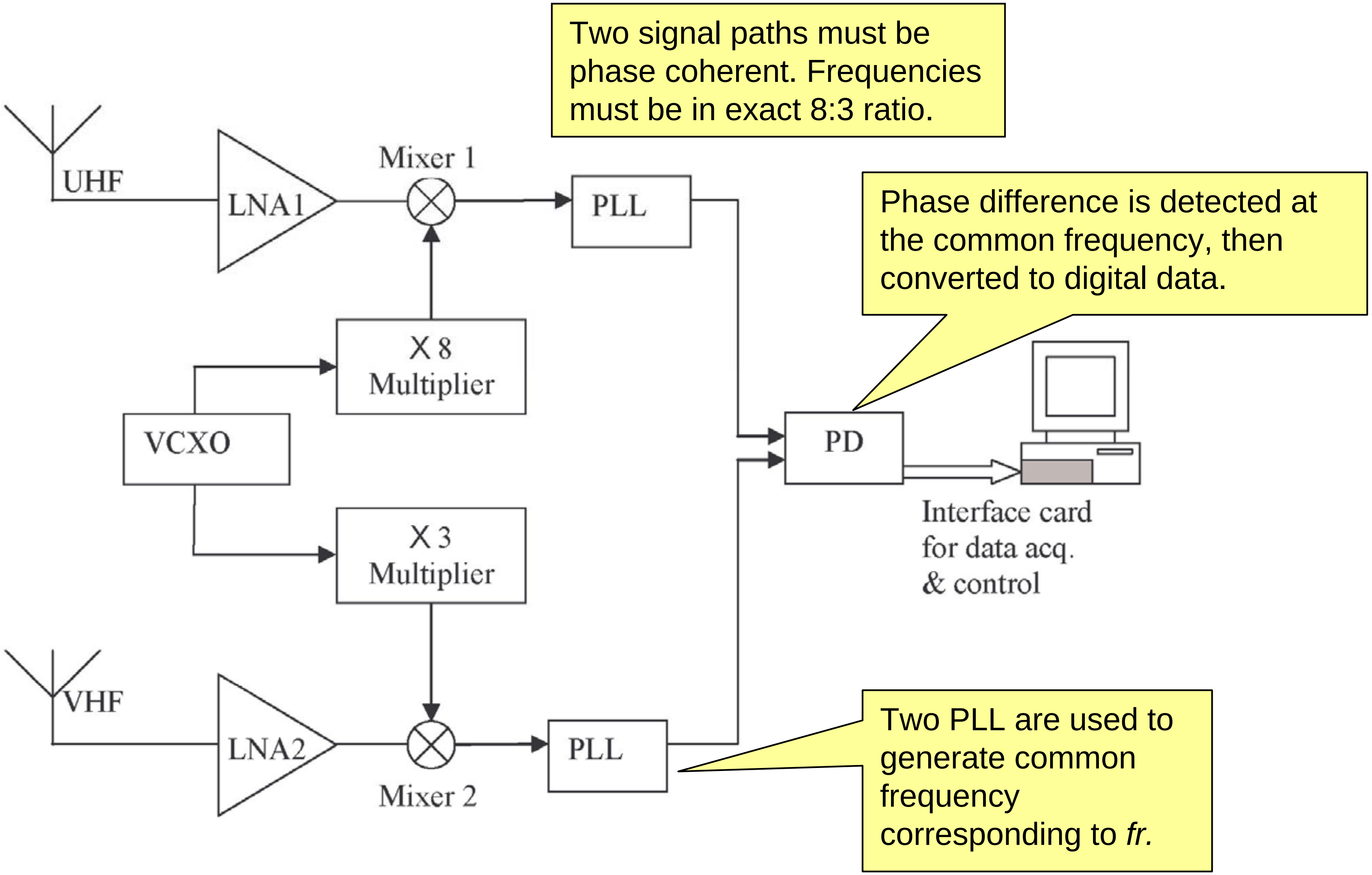
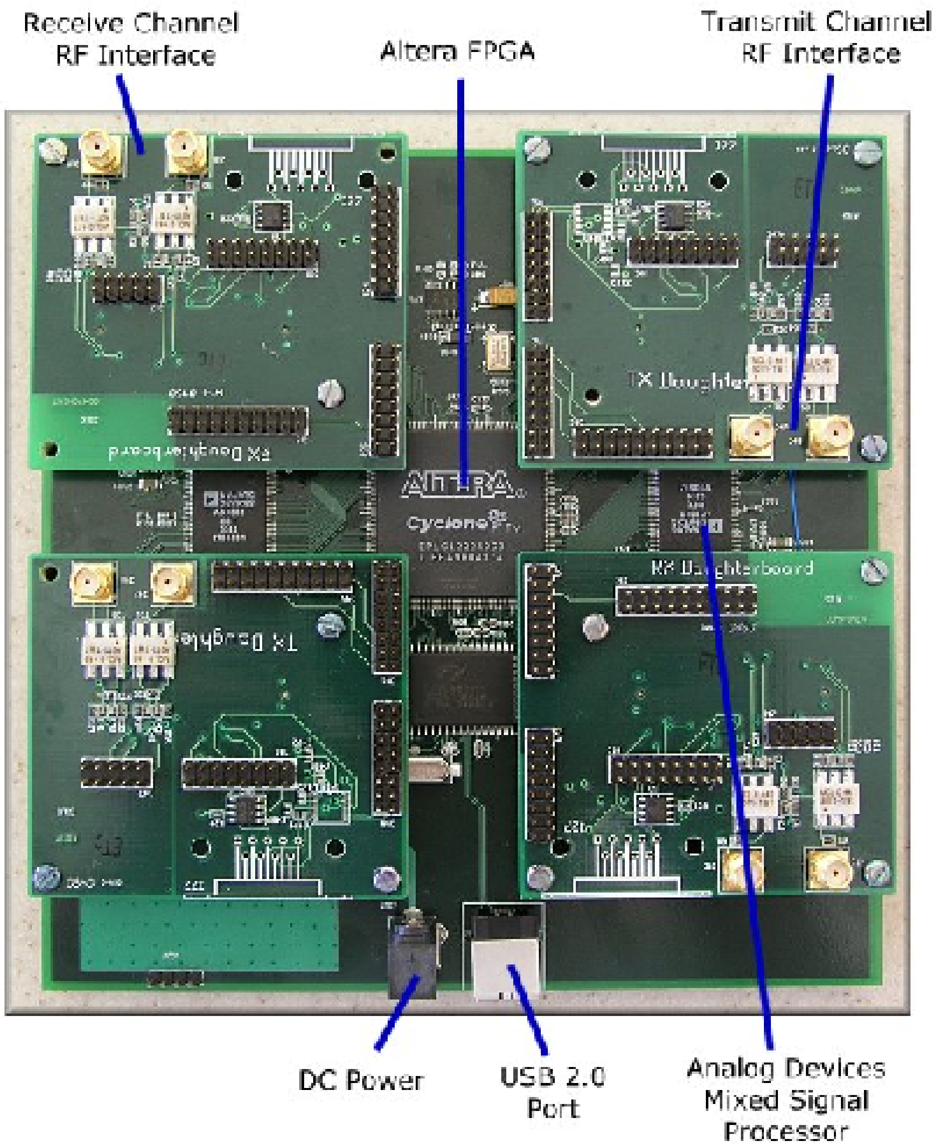



**Fig.2.2** *Simple block schematic of a coherent radio beacon receiver for LEOS reception*

From PhD thesis of Dr. S. Thampi, 2007

# GNU Radio and USRP




Picture of USRP

Main component of
our digital receiver is,

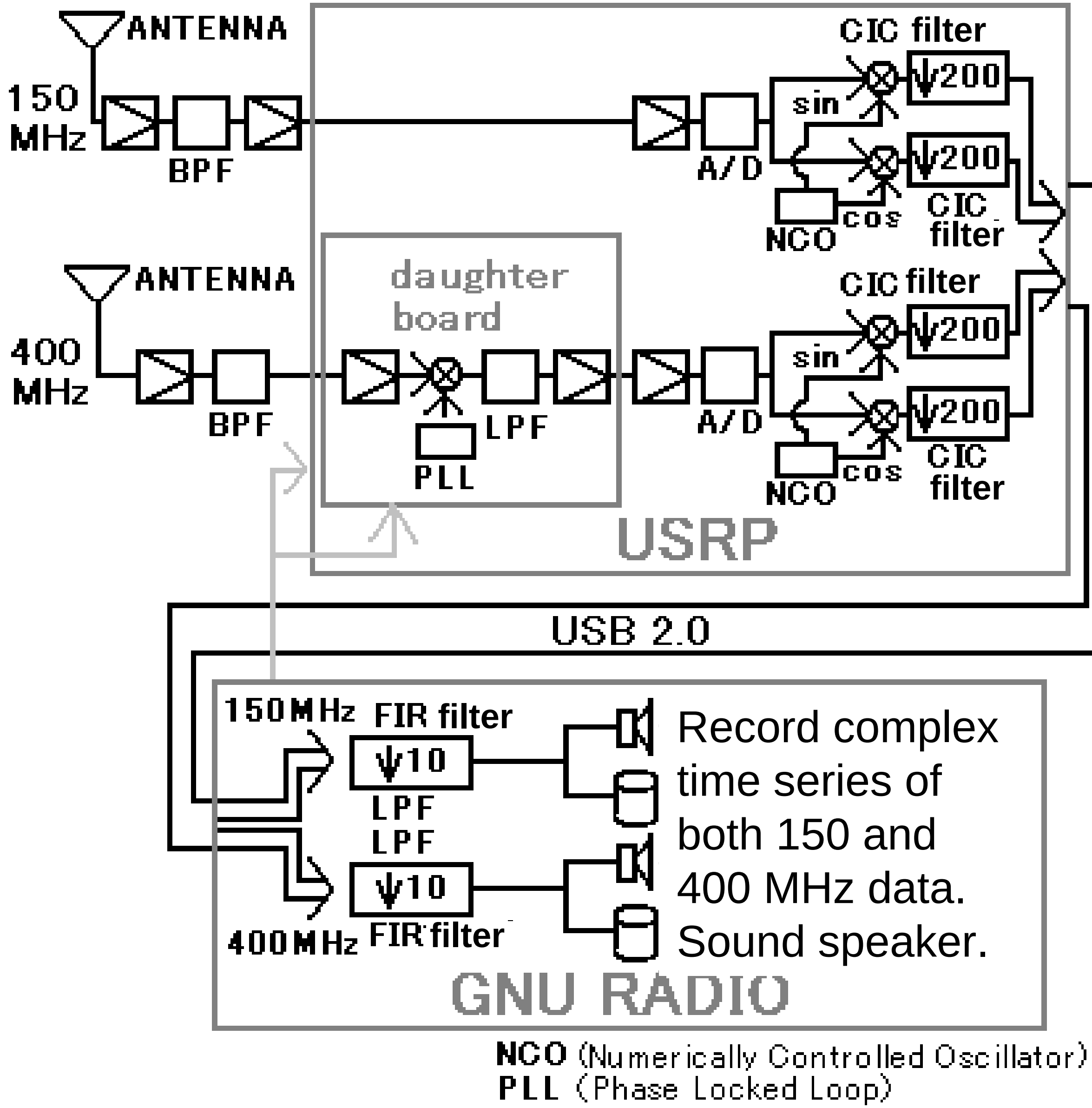
- LINUX PC
- GNU Radio
  Software toolkit for SDR (Software Defined Radio), a free software.
- USRP (Universal Software Radio Peripheral, see picture)
  A/D + signal processing board well associated with GNU Radio.

GNU Radio http://gnuradio.org/trac
USRP http://www.ettus.com

# Signal processing scheme

- Signal from 150/400MHz antennas are amplified with pre-amplifiers, and pass through BPF (= anti-aliasing filter), and fed to USRP daughter boards.
- Sampling: 12-bit A/D conversion at 64MHz on USRP board.
    - 150MHz： Direct under-sampling. As we can write 150MHz = 64MHz × 2 + 22MHz, the signal is regarded as 22MHz from software.
    - 400MHz: Analog down conversion is done at the daughter board. PLL on the daughter board is synchronized with the master clock of the USRP main board. Converted signal of about 10MHz is sampled on the USRP board.
- Demodulation： Digitized signals are multiplied with NCO (Numerically Controlled Oscillator) ‘SIN’ and ‘COS’ signals, and converted to base-band IQ signal. (Processing in FPGA on USRP)
- Decimation： CIC low-pass filtering and 200-times decimation is performed in FPGA.
- Signal transfer: The IQ signal (320kHz sample) is transferred to LINUX PC through USB interface.
- Further processing: On PC (GNU Radio), further FIR filtering and decimation (10 times) is conducted. IQ signals (32kHz sample) of 150 and 400MHz are stored in separated files. Both signals are fed into right and left speakers for monitoring.

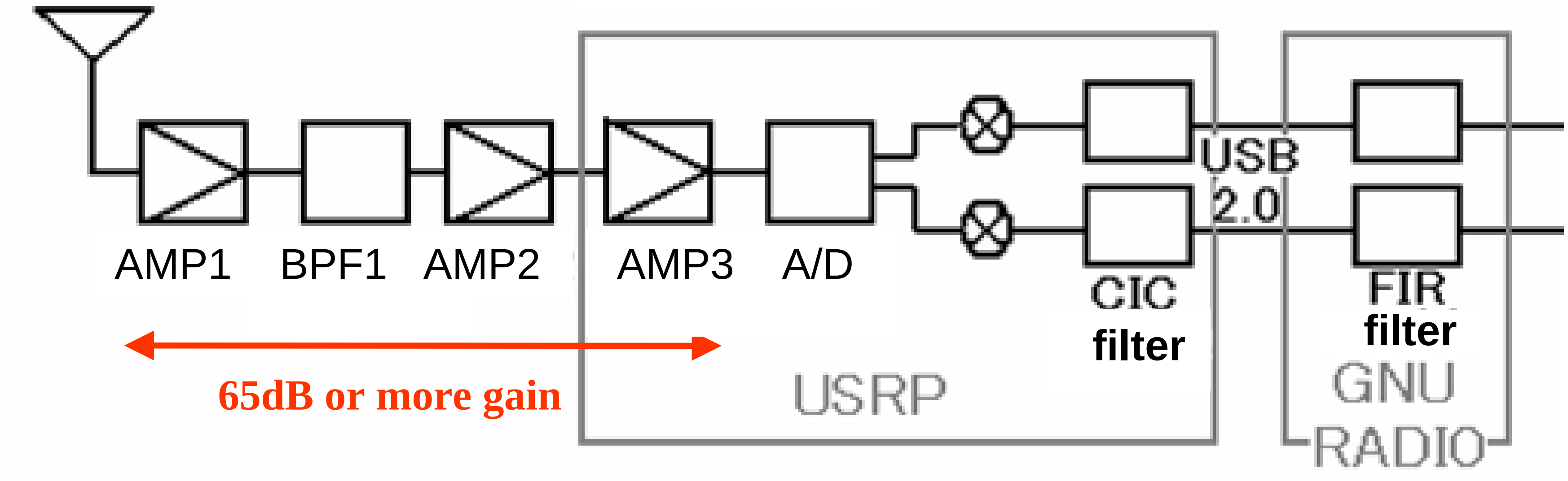
# Block diagram of the digital receiver




Signal processing on USRP board.

Signal processing in LINUX PC with GNU Radio under Python

# 150MHz close-up diagram



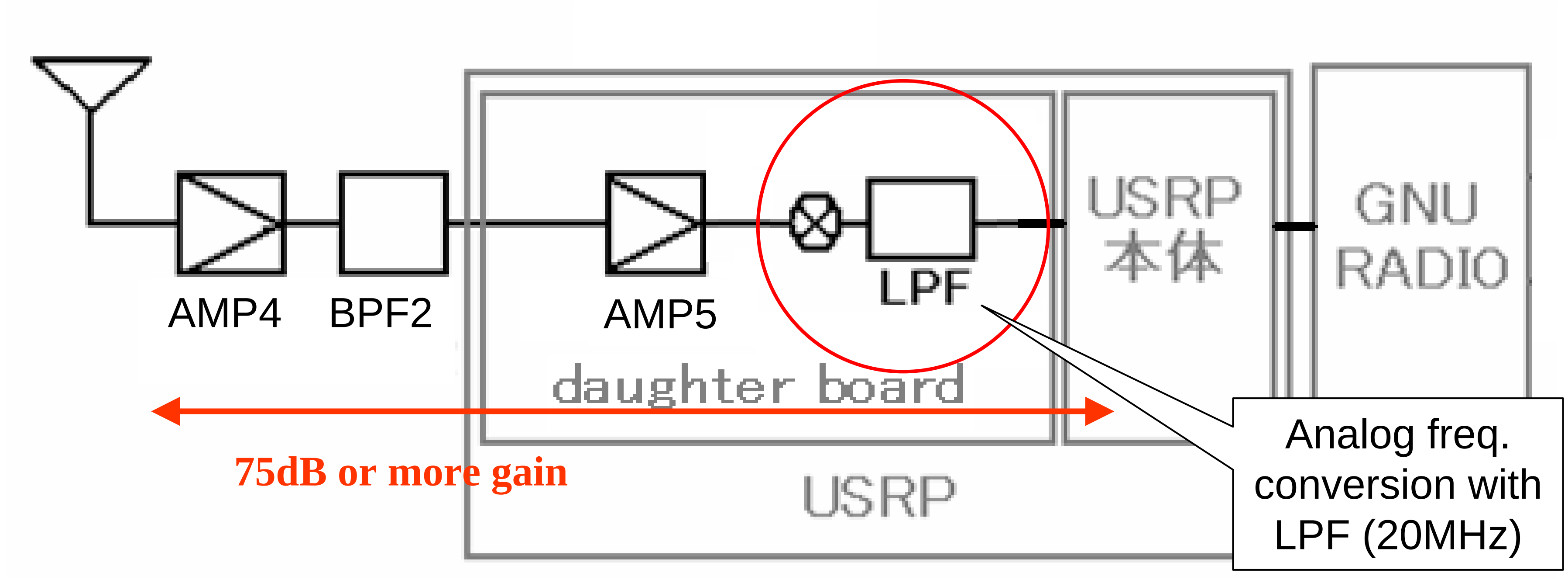

- ➢150MHz signal received by Basic-RX daughter board, and is directly sampled by A/D (64MHz, ±1V, 12bit).
- ➢Assume 0dB-gain antenna, we need 65dB or more gain before A/D.
- ➢USRP decimation factor is 1-256. In our application we select 200.
- ➢BPF1: center150MHz, pass-band 15MHz
- ➢Level diagram

  AMP1: about 18dB pre-amplifier (Hamtronics)

  AMP2: 28dB low-noise amplifier (mini-circuit)

  AMP3: 0-20dB programmable AMP on USRP main board

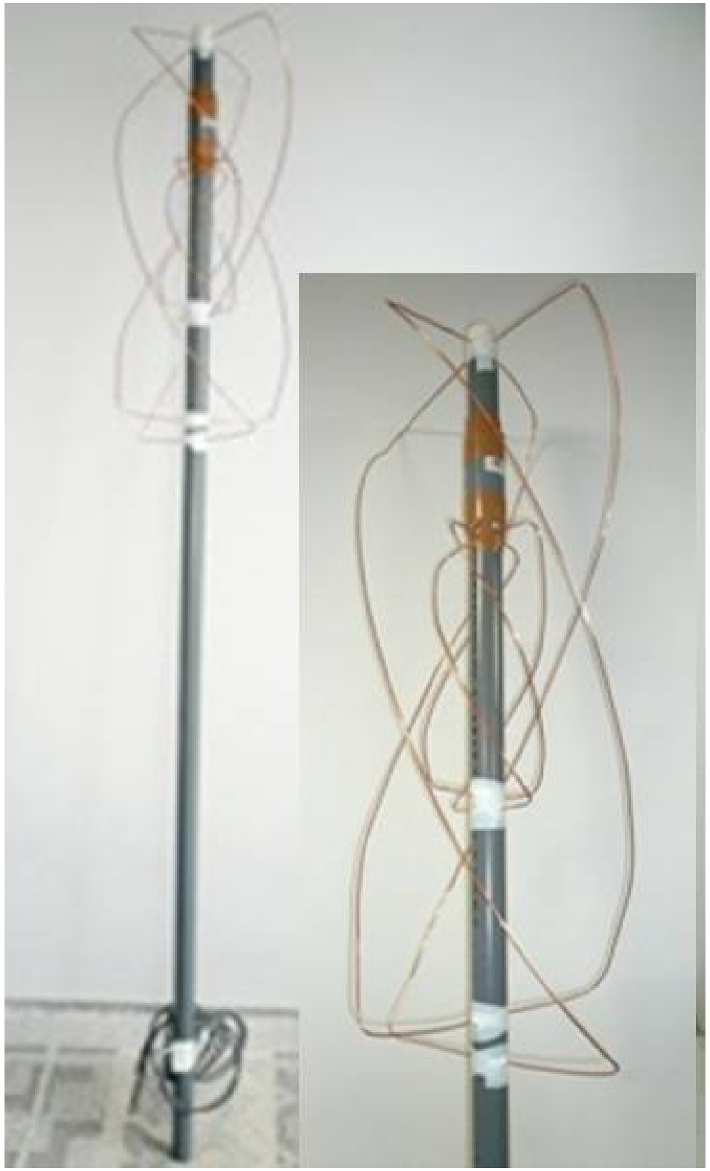
# 400MHz close-up diagram




- ➢400MHz signal is down converted on the daughter board (FLEX400) to 10MHz or less. A/D conversion is at the USRP mainboard (64MHz, ±1V, 12bit).
- ➢Assume 0dB-gain antenna, we need 75dB or more gain before A/D.
- ➢BPF2: center 400MHz, pass-band 20MHz
- ➢Level diagram

  AMP4 : about 18dB pre-amplier (Hamtronics)
  AMP5: 17.5-81.5dB programmable (USRP main + FLEX400 board)

# Antenna

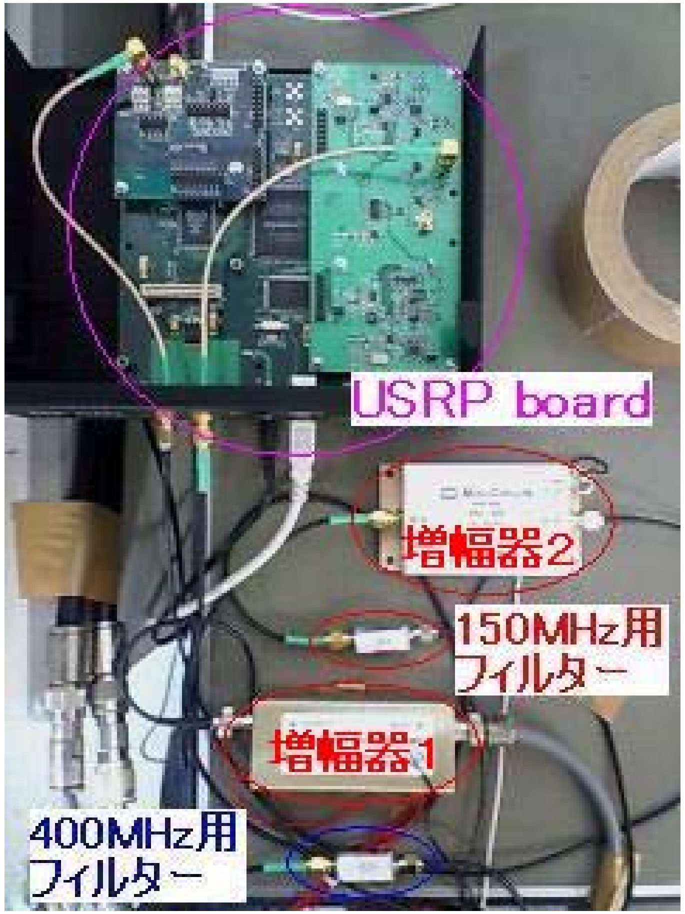



Pre-amplifiers

QuadriFilar Hericodoidal (QFH) antenna

We made simple QFH antenna for both 150MHz and 400MHz.

# Receiver




**USRP, amplifiers, BPFs**

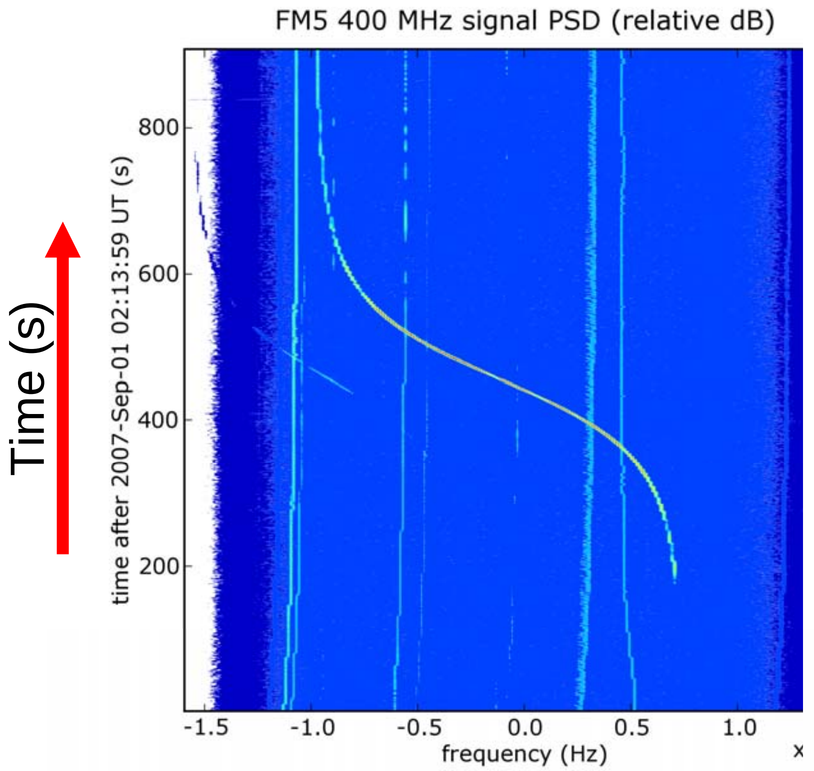

**Linux PC with GNU Radio**

# Example of satellite signal

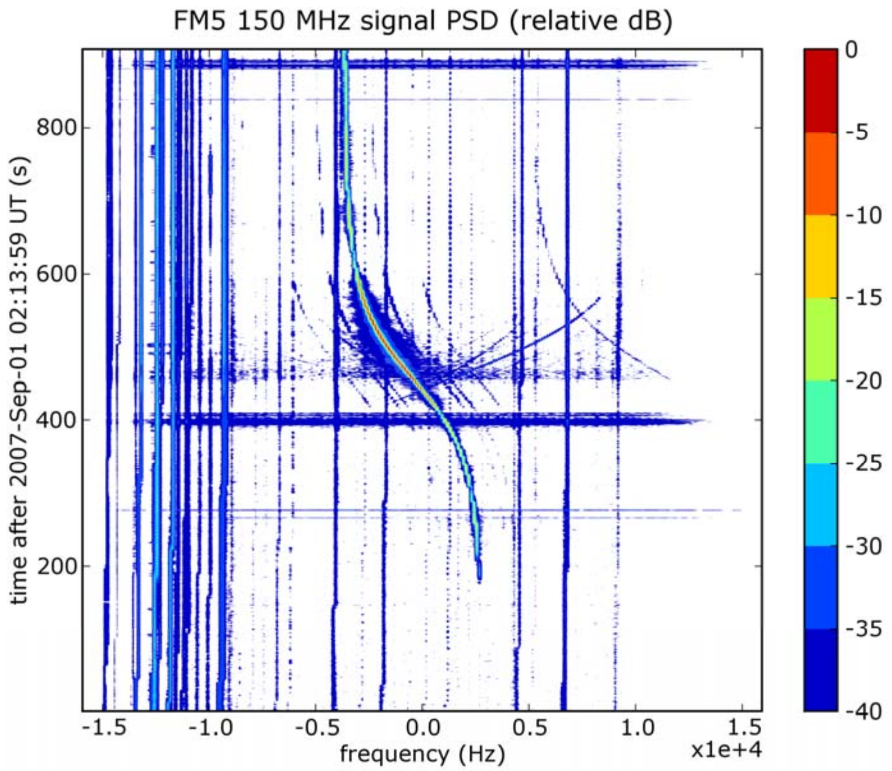
Location:
JAXA/USC (Uchinoura rocket range)

FORMOSAT-3 FM5

2007 September 1
02:13:59-02:29:07 UT
(daytime data)



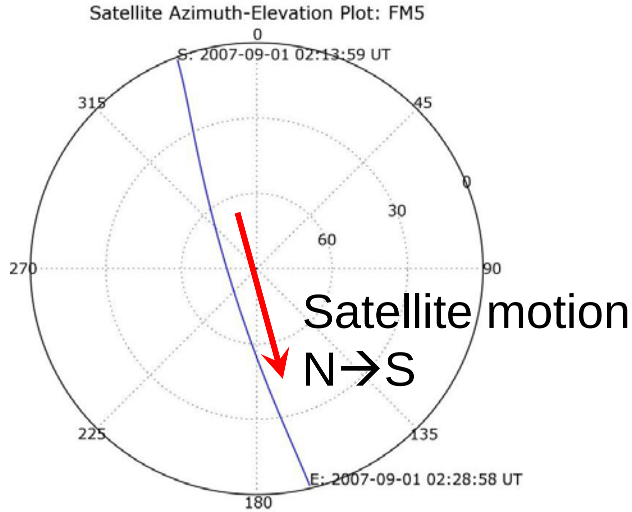

400MHz



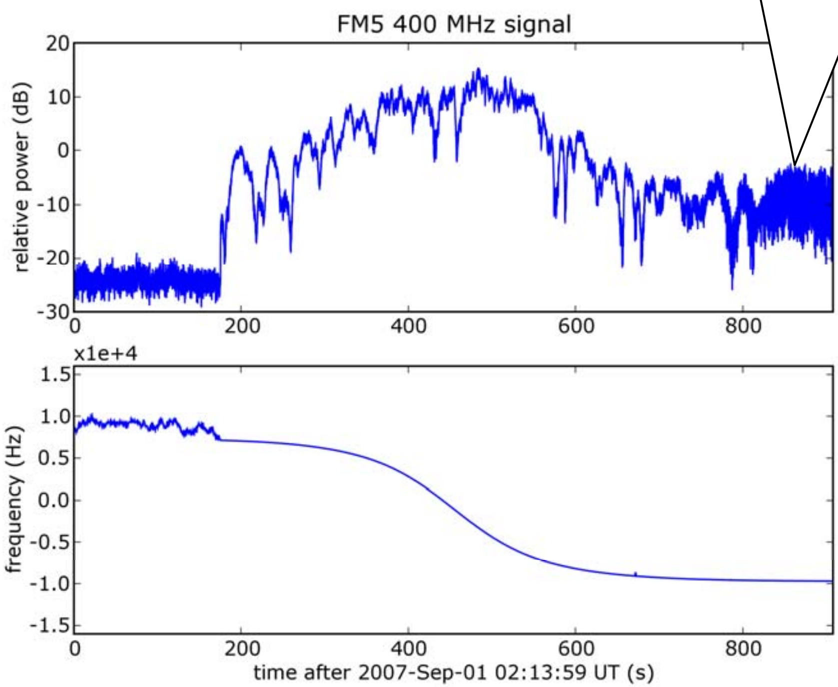

150MHz

FORMOSAT-3 FM5

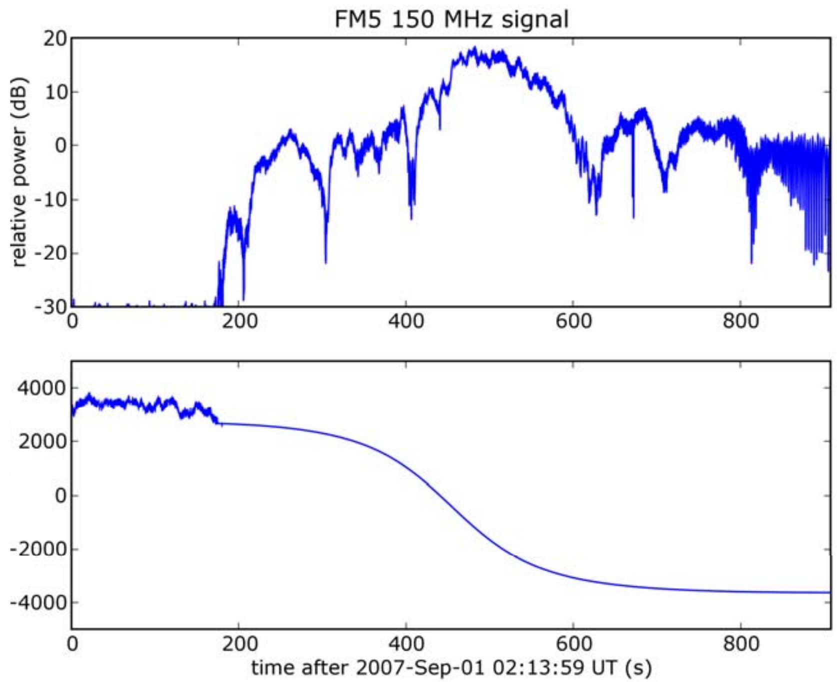
2007 September 1
02:13:59-02:29:07 UT
(daytime data)




This may be multipath fading due to sea surface reflection




400MHz intensity (up) and frequency (down)




150MHz intensity (up) and frequency (down)

# Estimation of TEC

We evaluated “differential Doppler” at $pqf_r$ (= 1200 MHz) frequency. This case,

$$pq\Phi = \frac{\pi A}{f_r C}\left(\frac{p}{q} - \frac{q}{p}\right)\int N\mathrm{d}s$$

1. From each spectrum (8192-point FFT) of the signal, 5 FFT components around the signal peak were selected. Narrow BPF-filtered time series are obtained by inverse FFT. (pass band = about 20Hz width. To avoid Gibbs effect, we shifted the time series by 0.5 length.)

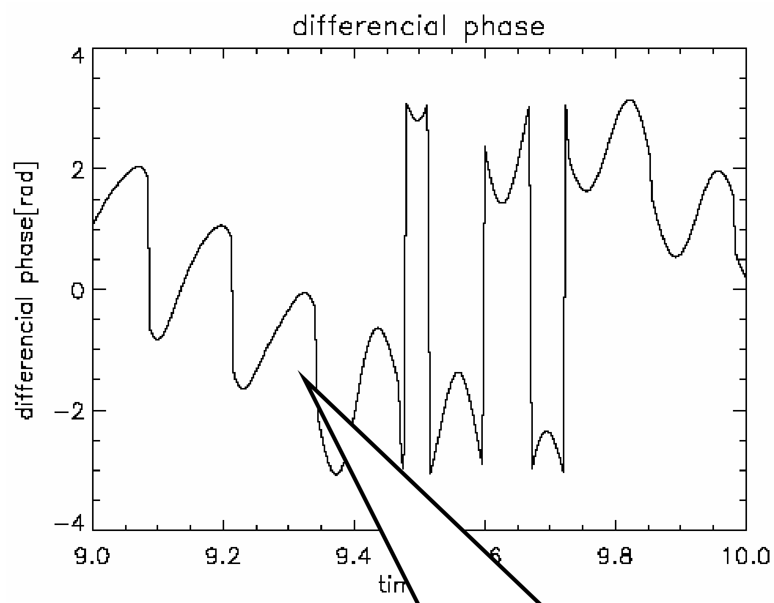
2. Phase difference was simply calculated by,

$$\frac{\text{(150MHz complex signal **8)}}{\text{(400MHz complex signal **3)}}$$

3. Then, unwrapping the phase, and obtained relative TEC.

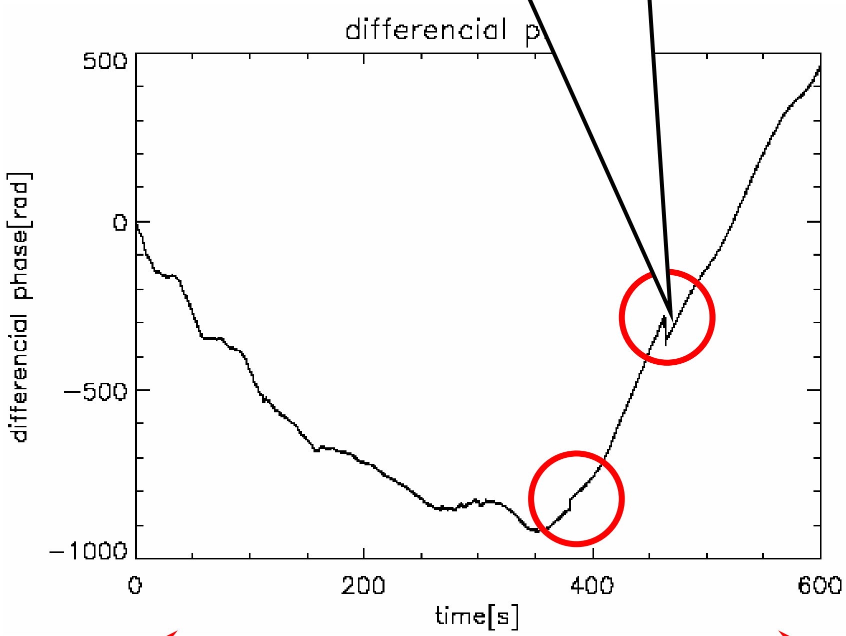
These glitches are often associated with temporal weak signal. They must be removed in later data analysis.

Differential phase at $pqf_r$ (=1200MHz)




Constant wavy fluctuation may not be real, but be generated by narrow filtering.

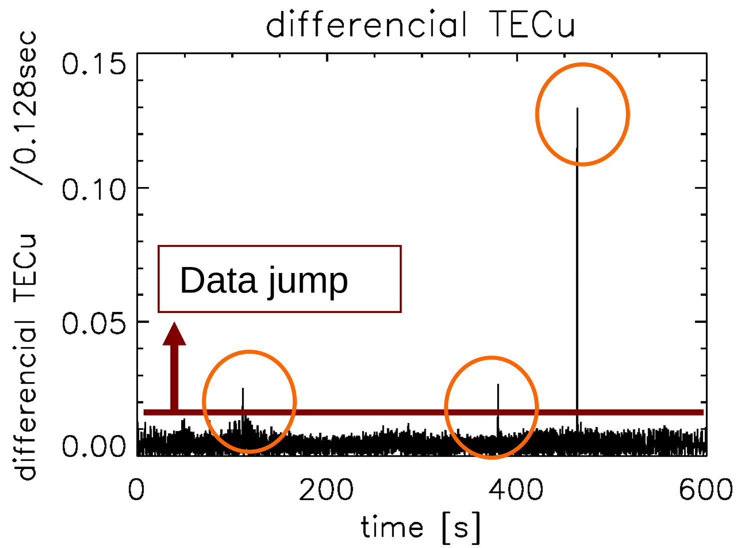
Unwrapped phase time series



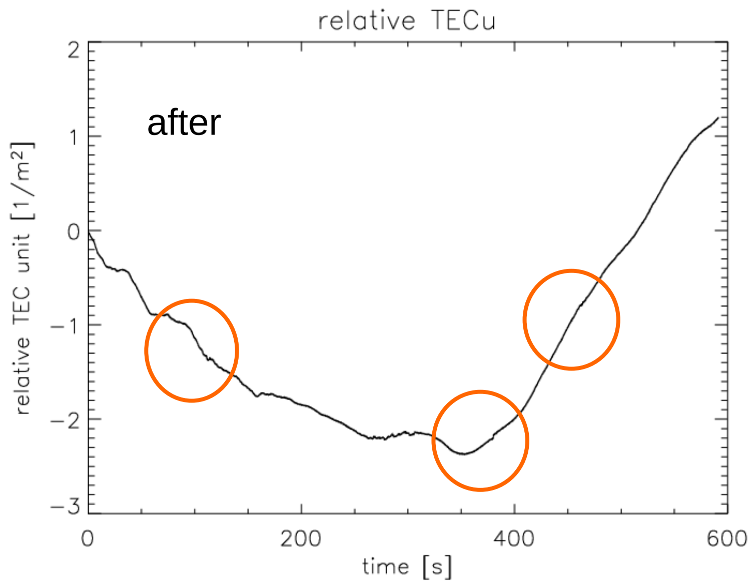

1 minutes

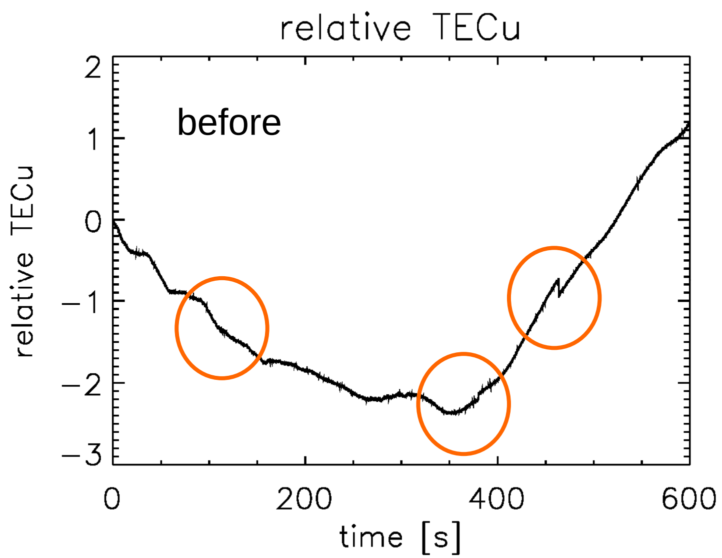
# Convert to TECu
# Remove of TECu jumps

TECu sometimes jumps. Many of them corresponds to drop-down of either signal intensity. We try to remove it, but the criteria is not established yet.




Differential of TEC in 0.128s
(am example criteria)



# Tuning error problem

NCO (Numerical Controlled Oscillator) on the USRP board cannot always tune to the exact frequency.

For the experiment in JAXA/USC, tuning error was,

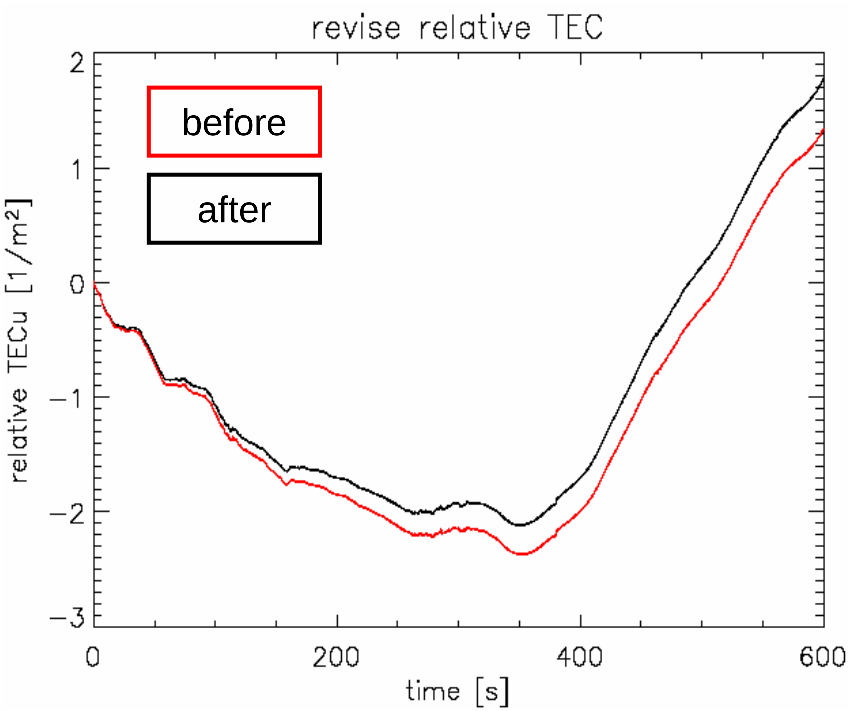
at 150MHz : 5.00679 mHz
at 400MHz : -1.54972 mHz

This corresponds to the differential phase of,

$8\,\Psi_{150} - 3\,\Psi_{400} = 0.281$ radian/second
$= -0.000726$TECu /second

We separately tested that this offset is stable, and removed it from the results.

It is possible to avoid this problem by choosing the appropriate NCO frequency.




Relative TECu before and after the tuning error removal.

(Note, this is different from offset of the absolute frequency. We experienced 5 ppm+ frequency offset of our USRP board.)

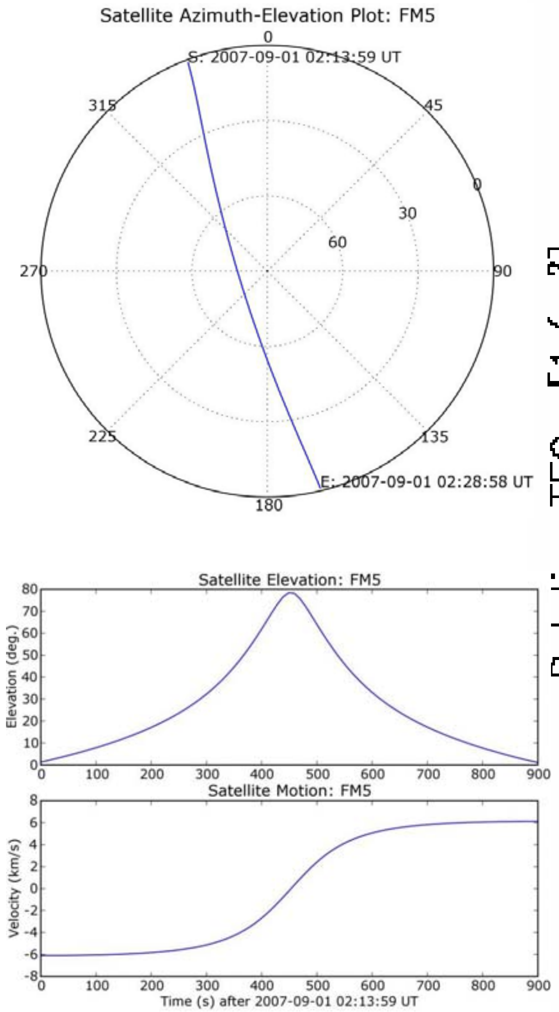
# Comparison with analog receiver

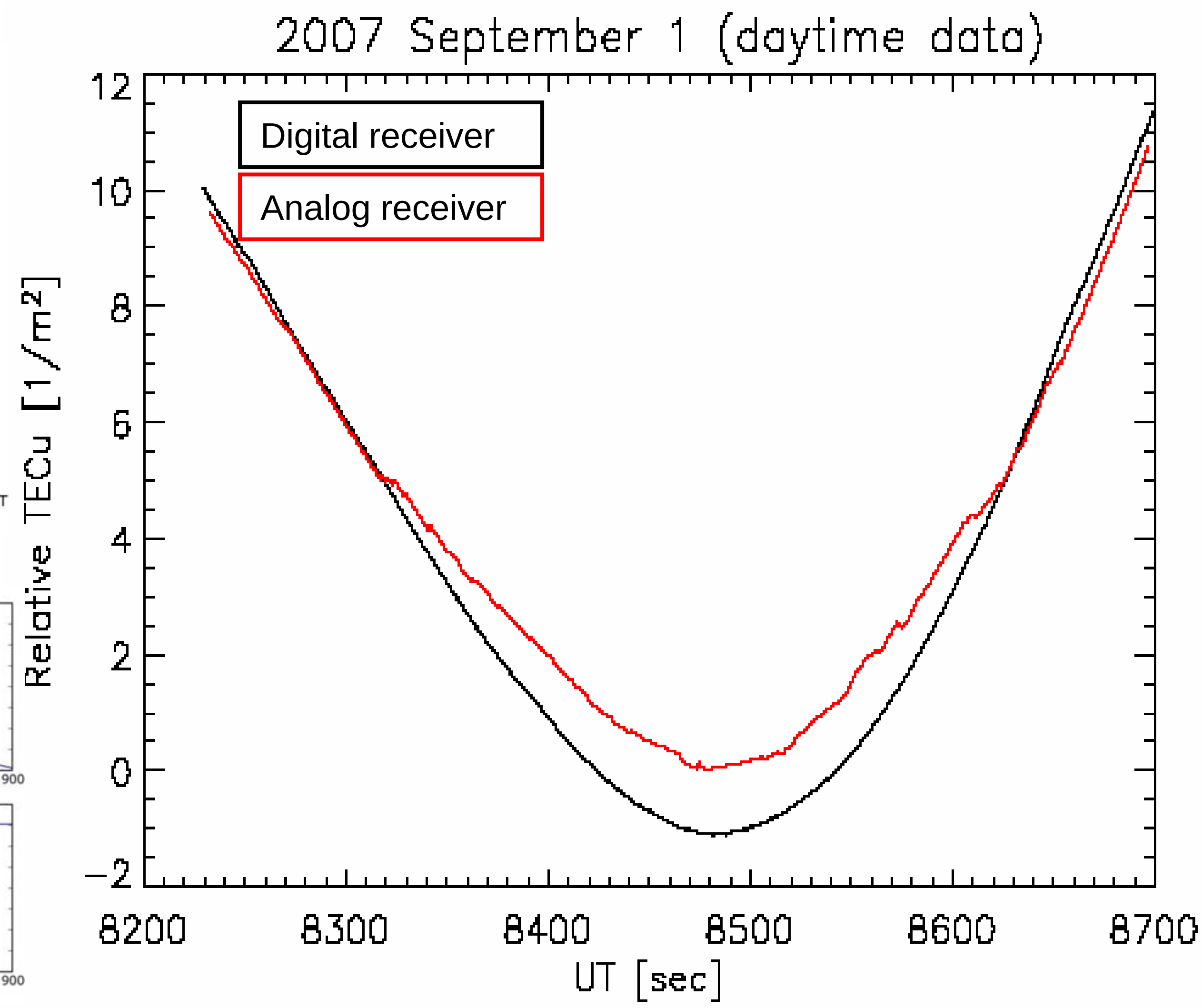
- Comparison with co-located analog beacon receiver, CIDR (Coherent Ionosphere Doppler Receiver) from Univ. of Texas at Austin. (courtesy of Dr. T. Garner)
- Location: JAXA/USC (Uchinoura Space Center)
  Period: August 31 and September 1, 2007.
  Satellite: FORMOSAT-3/COSMIC FM5

CIDR receiver + PC

CIDR antenna

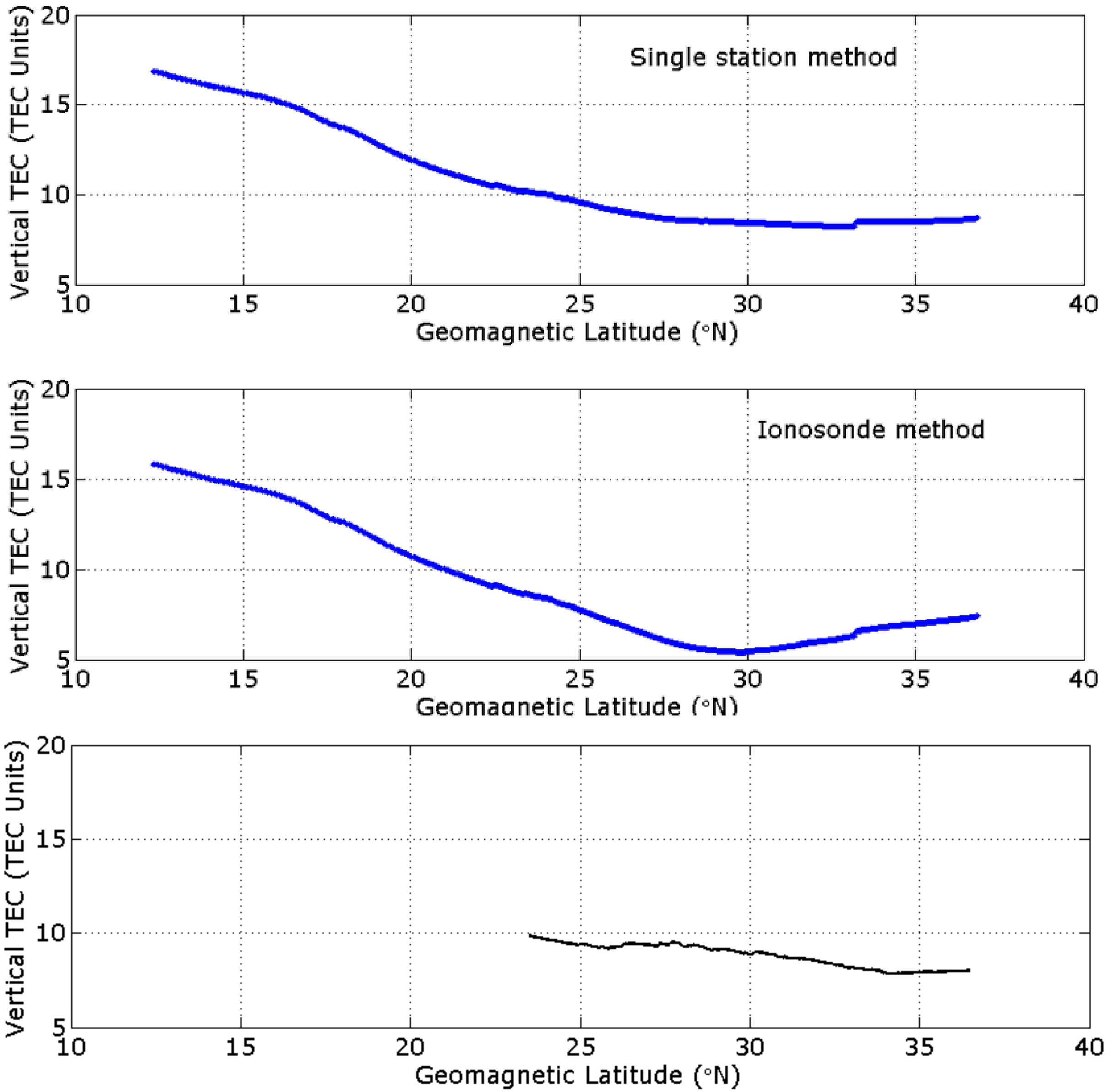
# Comparison of daytime data




2007 September 1, 2:17-2:25 UT

2007 September 01, 02 17UT-0225 UT

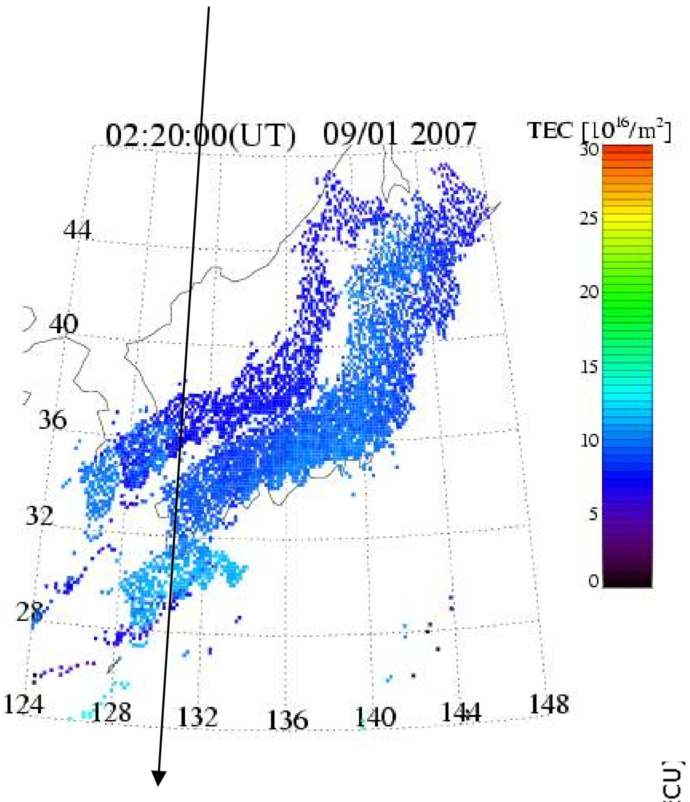



Some trial to estimate absolute TEC value.

Digital Rx

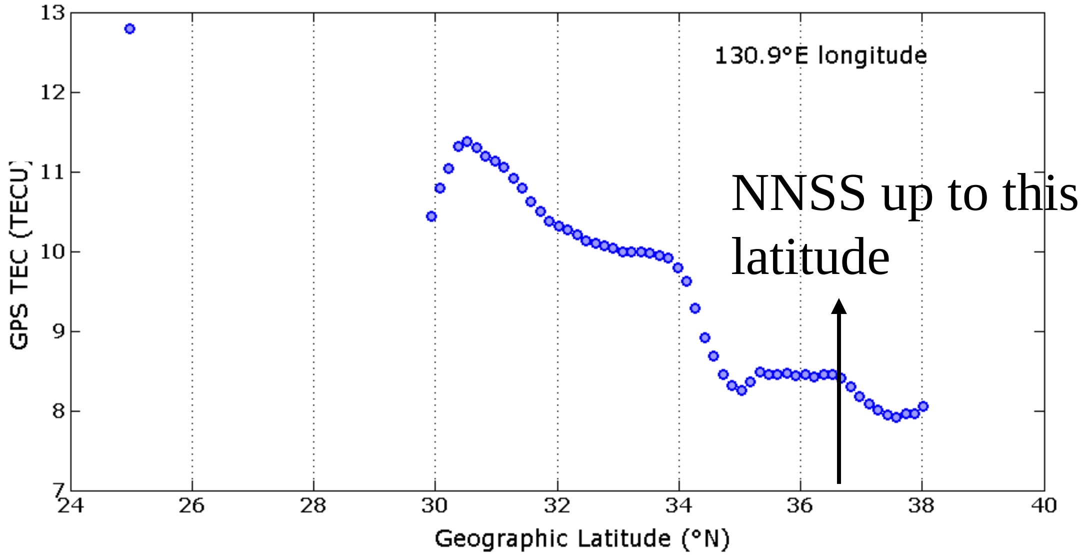
Analog Rx

Courtesy of
Dr. S. Thampi



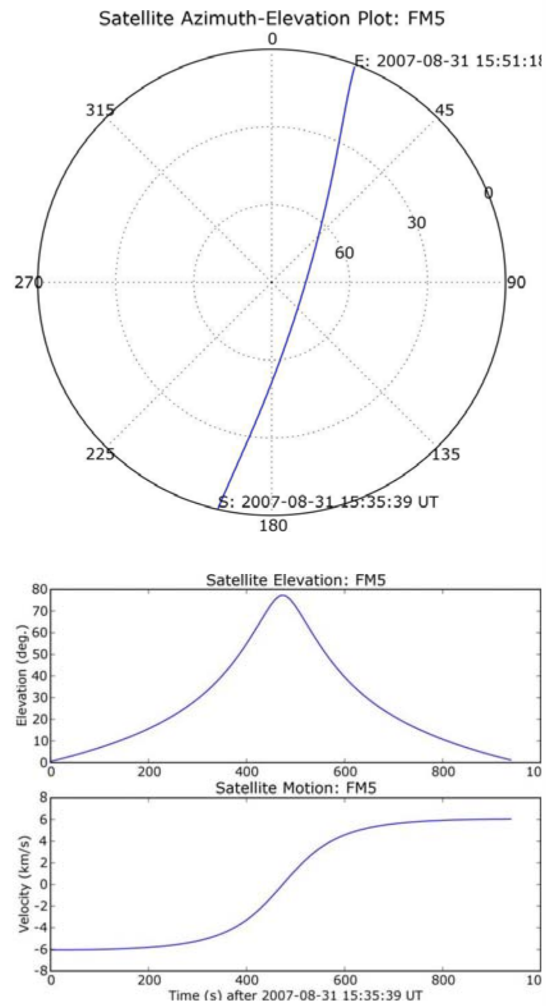

# Absolute TEC from GEONET GPS observations.

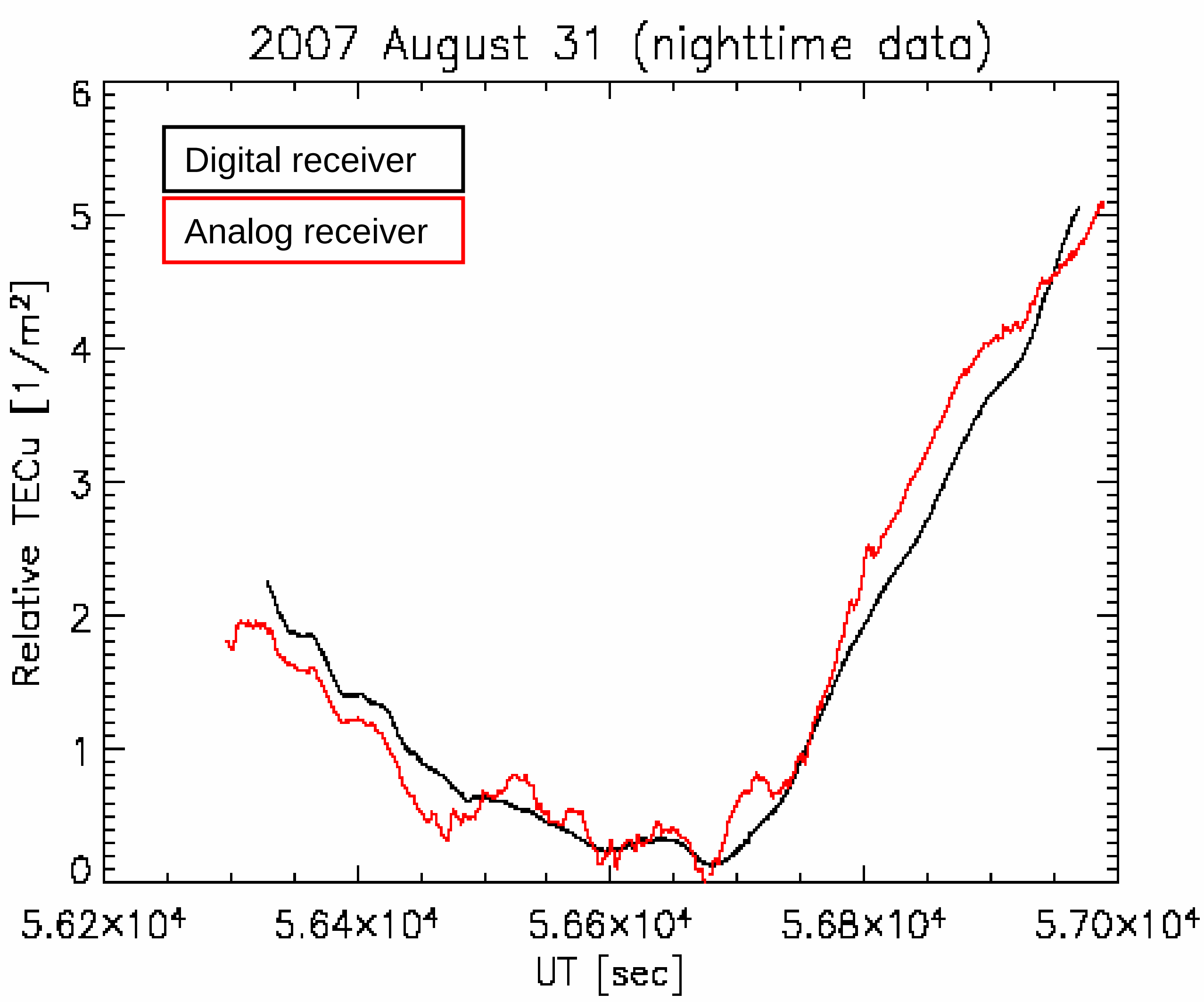
… Several TECu more than COSMIC results




2007 September 01 02 UT-03 UT (mean)

# Comparison of nighttime data

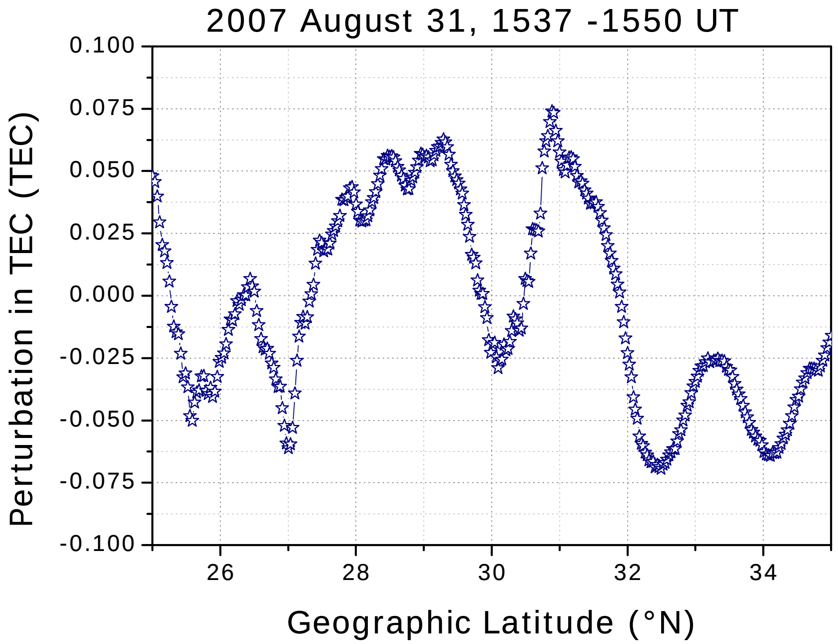



2007 August 31, 15:37-15:50 UT

# Wavelike structures in nighttime data

2007 August 31, 15:37-15:50 (UT)

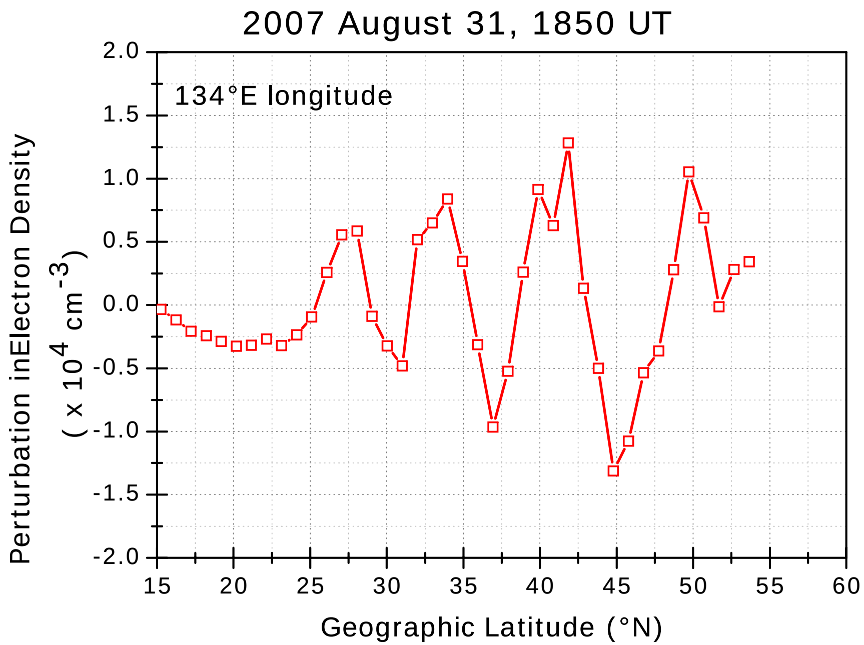



←Digital RX

Perturbation Component
(Single station method)

Nearby CHAMP data →

Perturbation Component
of CHAMP LP



# Summary (1)

- “GNU Radio + USRP” is found very good to compose 2-frequency (150/400MHz) digital beacon receiver.
- TEC was successfully estimated from phase difference between 150 and 400 MHz signals.
  - We evaluated the phase difference at 150MHz*8 400MHz*3 = 1200MHz. This made phase-flipping very fast.
- When signal was weak, phase was not well resolved, and resulted in jump of TEC values.
- Good comparison with CIDR (analog receiver) results.

# Summary (2)

- Why successful?
  - Stable and useful USRP + GNU Radio
  - Narrow but digital BPF
    (Digital filter is free from phase distortion.)
  - "No loop" signal processing might have improved time resolution.
- Next challenge
  - Networking and tomography
  - Simultaneous receive of multi-channel signals
  - "No trajectory forecasting" experiment
    (Useful for experiment in very rural area.)
  - More users (it's based on free hard/software)

# First plan of tomography experiment over Shigaraki (summer 2008)