AVON VLF/LF radio transmitter observation

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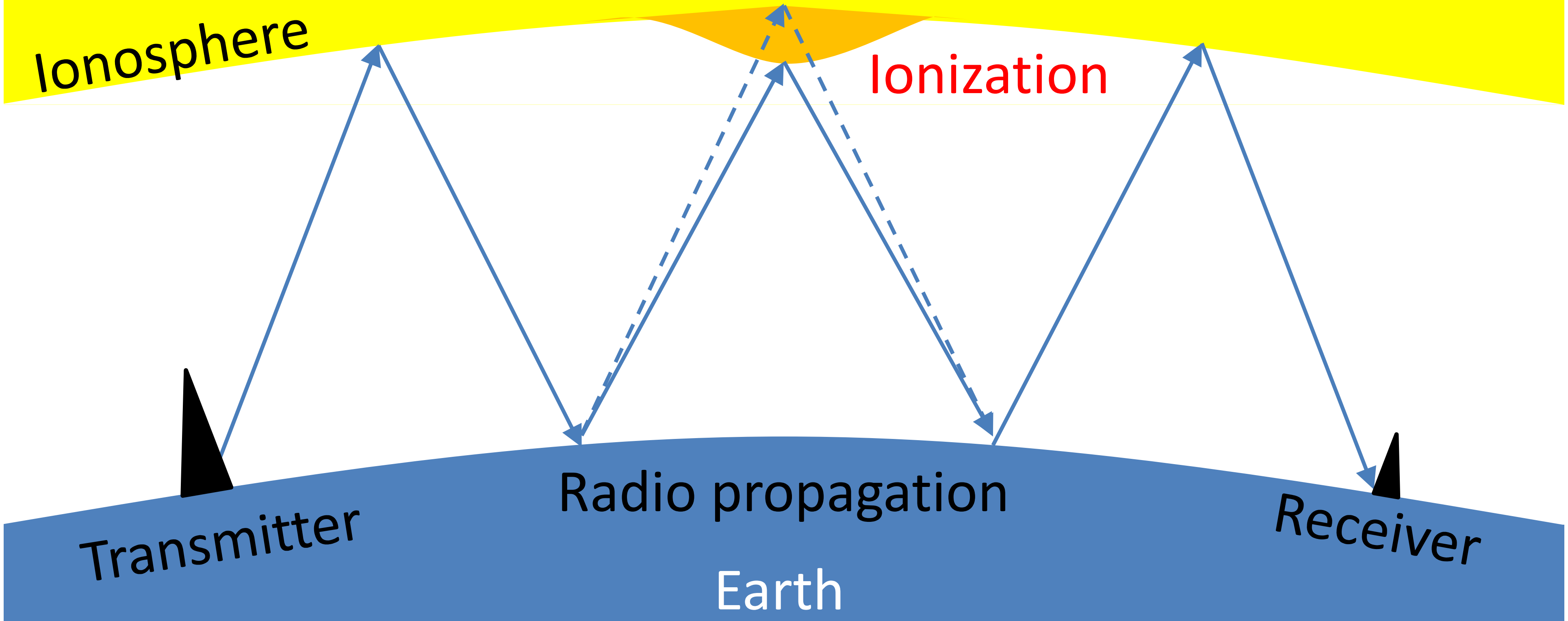
    - Early Trimpi (Lightning effect on the lower ionosphere)

Introduction

[1] What kind of information we can obtain from the VLF/LF radio transmitter observation?

Radio propagation between ground and lower ionosphere



Low frequency radio waves propagate at long distance reflecting between earth's surface and lower edge of ionosphere (70-90km, approx.).
Ionization change in the lower ionosphere causes to modify effective radio path length from a transmitter to a receiver and reflectance at the ionosphere. One can detect ionization phenomena as changes in received signal amplitude and phase.

Advantage and disadvantage of the radio transmitter observation

Advantage

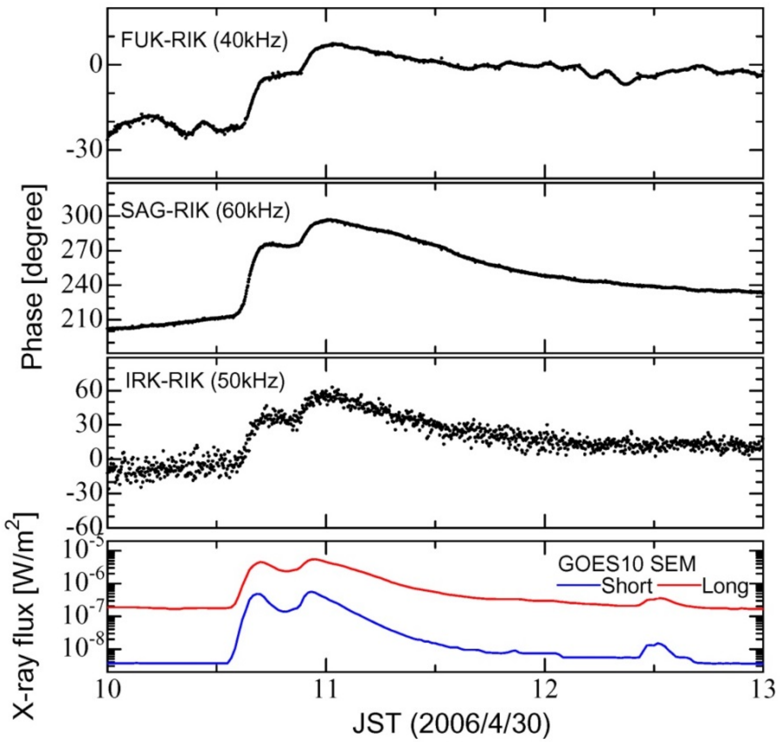
- Unique technique to probe lower ionosphere
- High time resolution compared with other observation techniques (optical and radar techniques, in-situ measurement by rockets)
- Possible to detect most of events occurred on radio propagation path
- Low cost instrument

Disadvantage

- No spatial resolution (network observation could resolve it)
- Physical quantities (such as density, temperature, ionization state) of the lower ionosphere are not directly obtained from the observation. Numerical models are needed to estimate physical quantities of the lower ionosphere

  ex) Radio propagation model is needed to find relation between changes in the ionosphere and radio signal received.

[1] Solar flare effect on the lower ionosphere

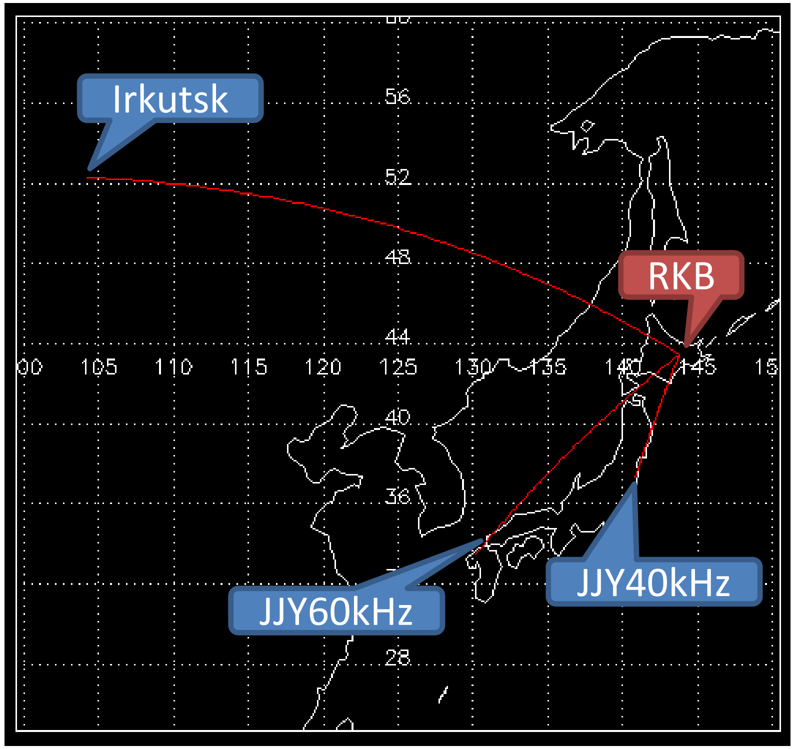


RKB - JJY 40kHz
(Fukushima)

RKB - JJY 60kHz
(Saga/Fukuoka)

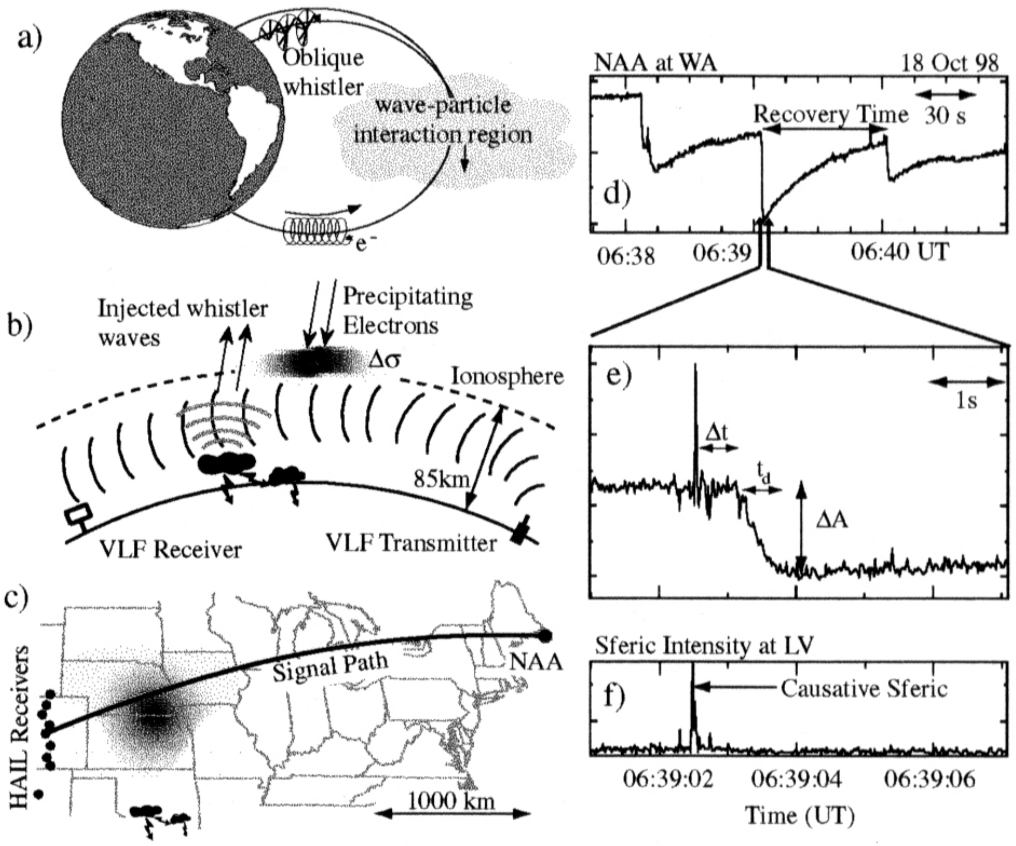
RKB – Irkutsk
(50kHz)

GOES
Solar X-ray flux
(NOAA/NGDC)



One of pronounced ionization phenomena observed by VLF/LF transmitter radio observation in mid/low latitude.

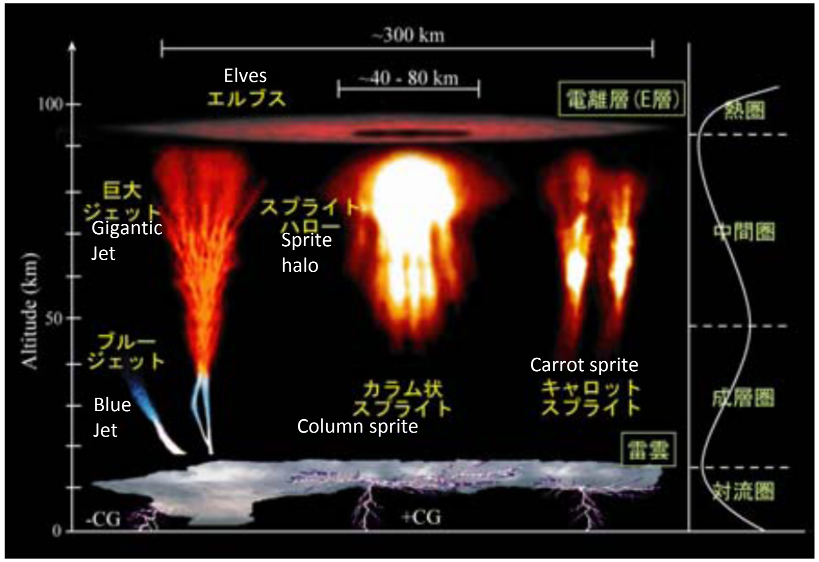
[2] Lightning induced energetic electron precipitation from radiation belts



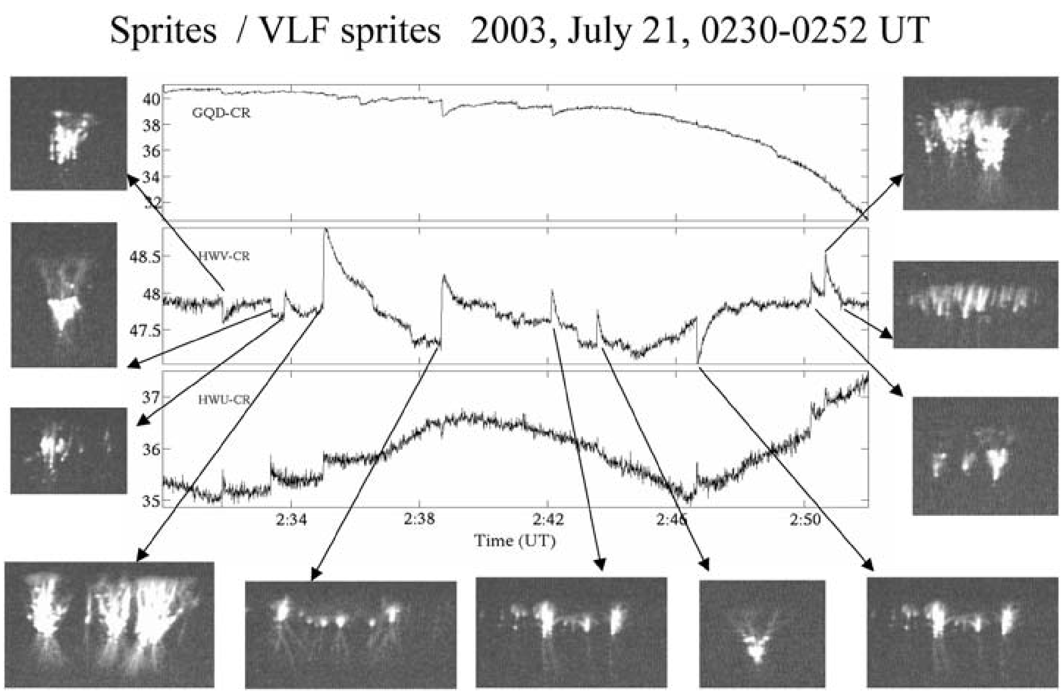
Johnson et al. 1999

- As particle density is so tenuous outside the atmosphere, collision between particles are negligible.
- Instead, electromagnetic waves are responsible for scattering particle's orbit.
- Lightning induced waves scatter high energy electrons trapped near earth space(radiation belt), some electrons precipitate into the atmosphere (figs. a and b).
- The precipitation occurs for short time duration (t_d in fig. e). It causes ionization in the lower ionosphere and changes amplitude and phase in received transmitter radio signal (figs. e and f)
- The ionization recovers slowly (fig. d) as decreasing ionization state (due to attachment of electrons with surrounding molecular and recombination process).

[3] Lightning effect on the lower ionosphere



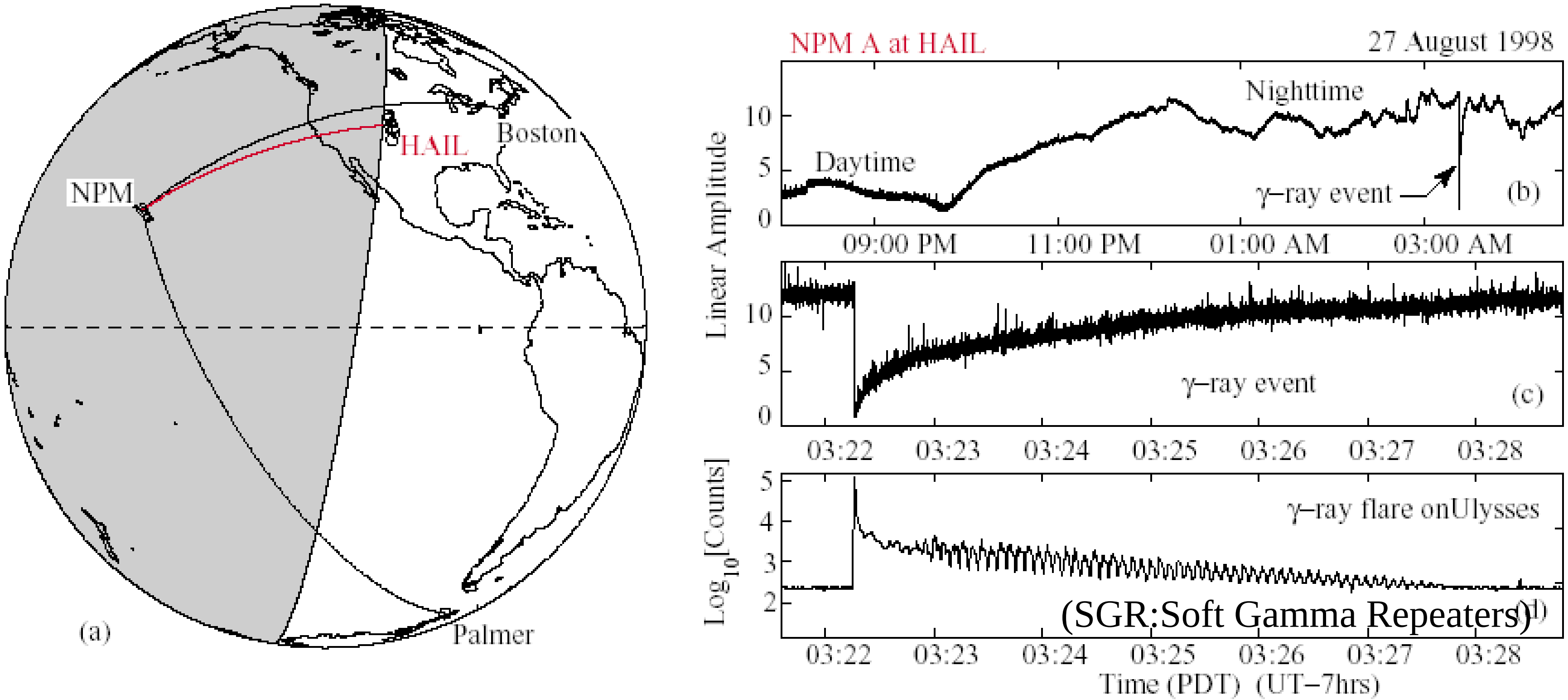
Schematic picture of transient luminous events (TLEs) (M. Sato)



One-to-one correspondence of red sprites & VLF perturbations observed in Europe (Mika & C. Haldoupis 2008)

- Direct ionization in the lower ionosphere due to lightning produced quasi-static electric field and electro-magnetic pulse.

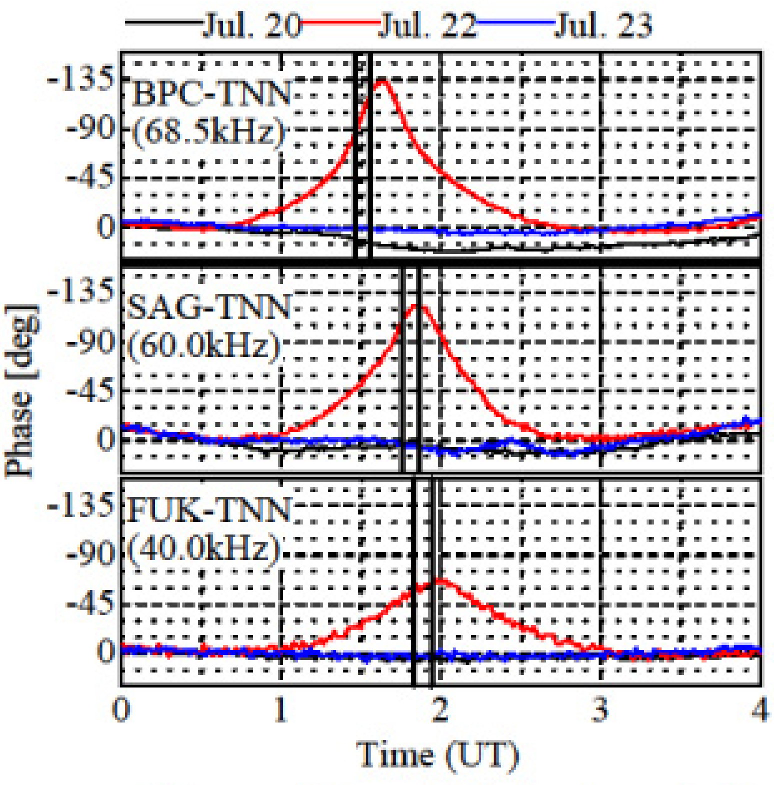
[4] Gamma ray burst



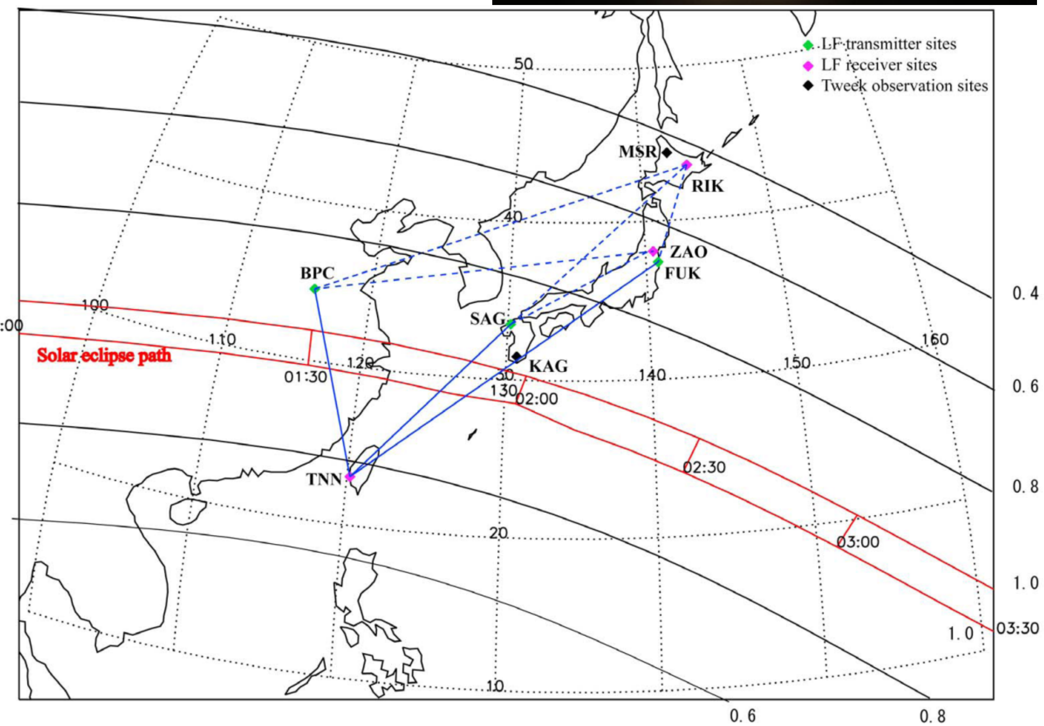
γ-ray flare (SGR1900+14) measured by Ulysses spacecraft (bottom) and radio transmitter (top and middle) (Inan et al. 1999).

[5] Solar eclipse

- Solar eclipse also affects VLF/LF subionospheric propagation as the eclipse causes to decrease ionization state in the ionosphere and change effective reflection height of radio waves.



Phase variations of LF signals received at the Tainan station (TNN)



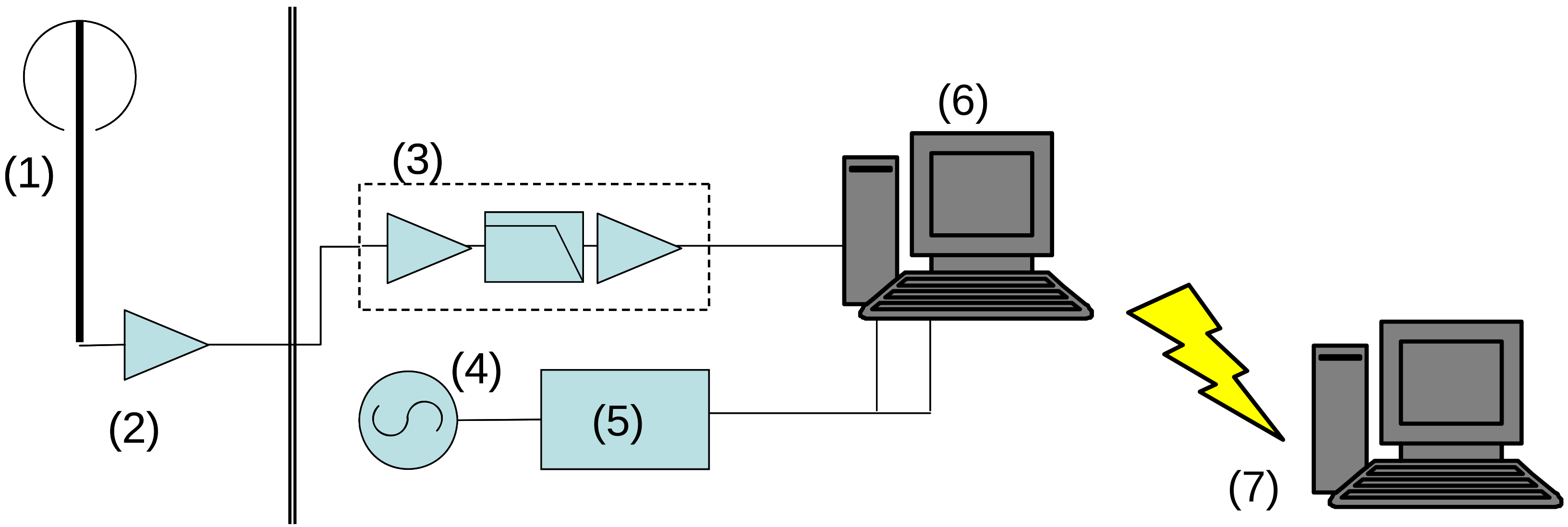
Ohya et al. 2012

Introduction

[2] VLF/LF radio transmitter observation

(in the case of AVON)

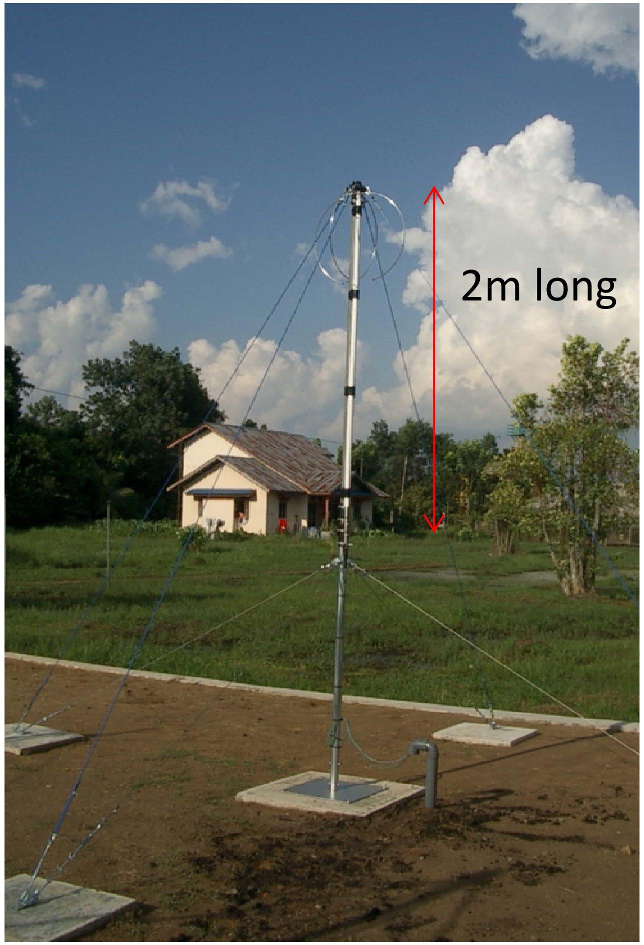
Overview of instrument



(1) Radio antenna
Vertical monopole or magnetic loop
(2) Pre-amplifier (low noise)
(3) Main-amplifier
Variable gain
Anti-aliasing low-pass-filter
(4) GPS locked oscillator
10MHz and 1PPS output

(5)Decimation
10MHz to 200kHz (sampling clock)
(6)A/D converter and PC
200kHz sampling /16bit
Real time FFT analysis
Recording transmitter signals, 10Hz
(7) Data server (Tohoku-U, Sendai Japan)

Some photographs (Pontianak)



Vertical electric monopole antenna (LF4060)

GPS receiver(left) and antenna indoor unit

Transformer, UPS, PC, and back-end receiver (from left to right)

Cost to build a VLF/LF radio transmitter receiving system

Radio antenna	50,000-100,000 JPY
GPS antenna & receiver	50,000-200,000 JPY
Personal computer	50,000-100,000 JPY
A/D card	100,000 JPY
Receiver (self-produced) and cables	<50,000 JPY
<u>Total Cost</u>	<u>300,000-550,000 JPY</u>

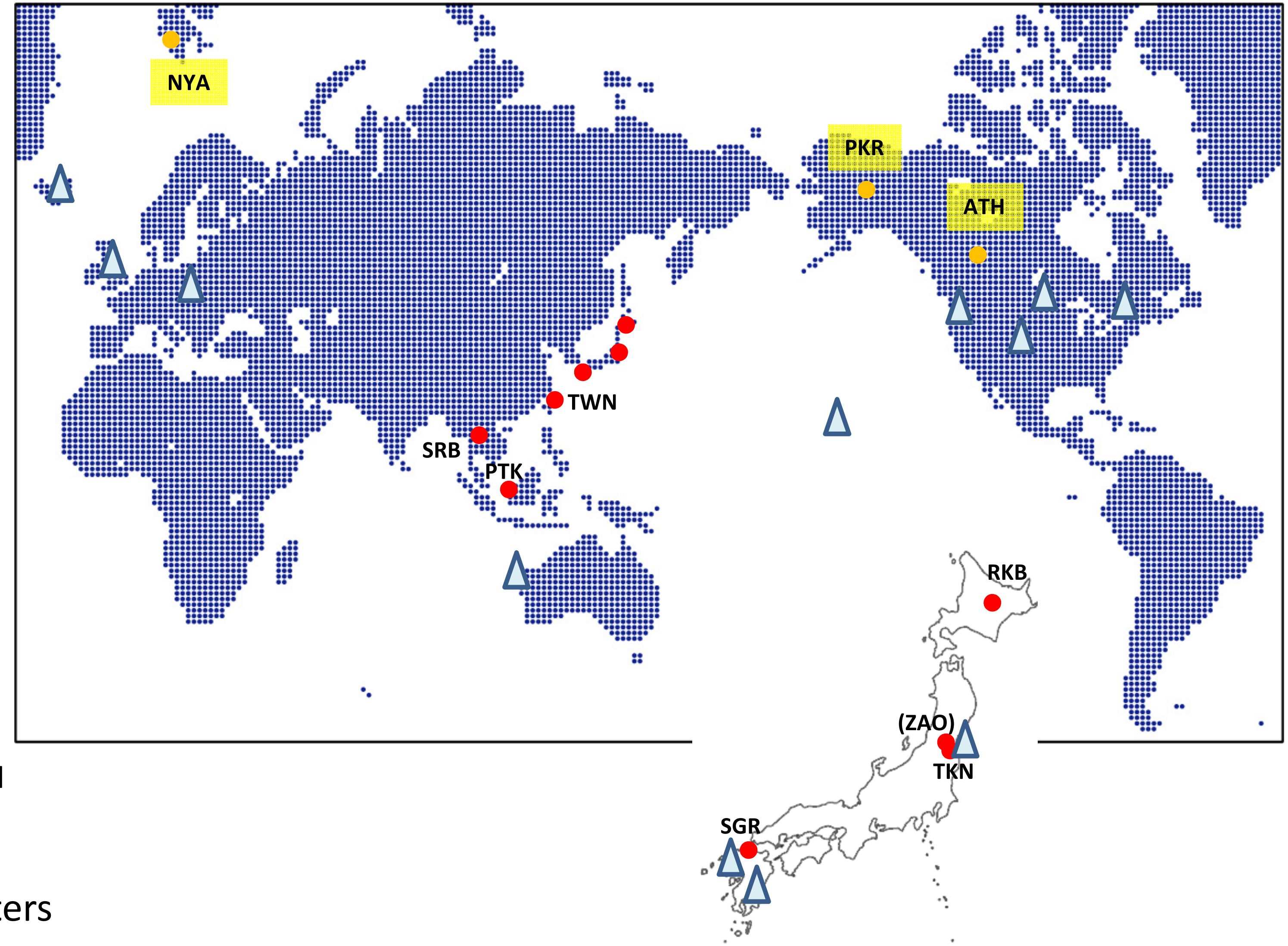
Location of VLF/LF radio receivers (both AVON and non-AVON stations)

Station list

- ATH: Athabasca
- NYA: Ny Alseund
- PKR: Poker Flat
- PTK: Pontianak
- RKB: Rikubetsu
- SGR: Sasaguri
- SRB: Saraburi
- TKN: Takine
- TWN: Tainan
- ZAO: Zao*

(Red: AVON station)

*Receiver at ZAO moved to TKN since Dec. 2014



Major transmitters

Data availability and format

- Data format
  - Three kinds of data format depending on station and observation period. See Appendix A in detail.
  - Ver.1.0 gzipped ascii format (staYYYYMMDDHH.dat.0.gz)
  - Ver.1.1 gzipped ascii format (staYYYYMMDDHH.dat.gz)
  - Ver.2.0 binary format (STAYYYYMMDDHH.dat)

  sta/STA: station code (ex. PTK:Pontianak)

- Data availability
  - See Appendix B

Practical training

[1] Obtaining AVON LF transmitter data

Quick look and data archive

- Quick look (24-hour plot)
  - For Ver1.0/1.1 data

    http://iprt.gp.tohoku.ac.jp/lf/ql_lf.php
  - For Ver2.0 data

    http://iprt.gp.tohoku.ac.jp/lf/ql2_lf.php

- Data request
  - Contact to F. Tsuchiya (Tohoku-U, Japan) (tsuchiya@pparc.gp.tohoku.ac.jp)

Data and tools for winter school 2015

- Data and IDL code in USB-memory
  - Copy “AVON” folder in USB memory to the top of C drive (C:¥)
  - Add the directory “C:¥AVON¥IDL¥” to the IDL path
- Structure

```
AVON--------LF------- ver1    : Sample data with Ver1 format
                      ver2    : Sample data with Ver2 format
                      wwlln   : Sample WWLLN data
                      gose    : Sample GOES X-ray data
            IDL------ LF      : IDL code for the LF data
                      LIB     : General libraries
                      log     : Command log for winter school
                      (you can copy commands in the log file and
                      paste them in your IDL command prompt.)
```

Practical training

[2] Example of data analysis

Solar flare and lightning effects in the lower ionosphere

Practical training
[2-1] Data analysis/solar flare effect

- Target : Solar flare effect
- Data source : AVON Pontianak station
- Other data source : GOES-15 X-ray flux data
  - Downloaded from http://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html
- Date/Time: Jul. 11, 2012
- Overview of data analysis
  - Plot radio path from BPC 68.5kHz transmitter to Pontianak
  - Reading BPC data measured at Pontianak
  - Plot the BPC phase data after noise filtering
  - Obtaining and reading GOES X-ray flux data
  - Compare the transmitter signal with the x-ray flux

(1/5) Plot radio propagation path from BPC 68.5kHz transmitter to Pontianak (PTK)

Command list : C:¥AVON¥IDL¥log¥ training_1.pro

- Plot coast line map which include a transmitter(BPC) and receiver (PTK)

```
IDL>  window, 0, xsize=500, ysize=500
IDL>  map_set, limit=[-10.0, 90.0, 40.0, 130.0], /cylindrical
IDL> map_grid, /label
IDL> map_continents,/continents, /hires
```

- Calculate Radio propagation path (Great circle path)

```
IDL> src = [115.83,34.63]  ; longitude and latitude of BPC
IDL> trg = [109.367,0.003]  ; longitude and latitude of PTK
IDL> lf_get_gcp, src=src, trg=trg, gcp_lon=lon, gcp_lat=lat
```

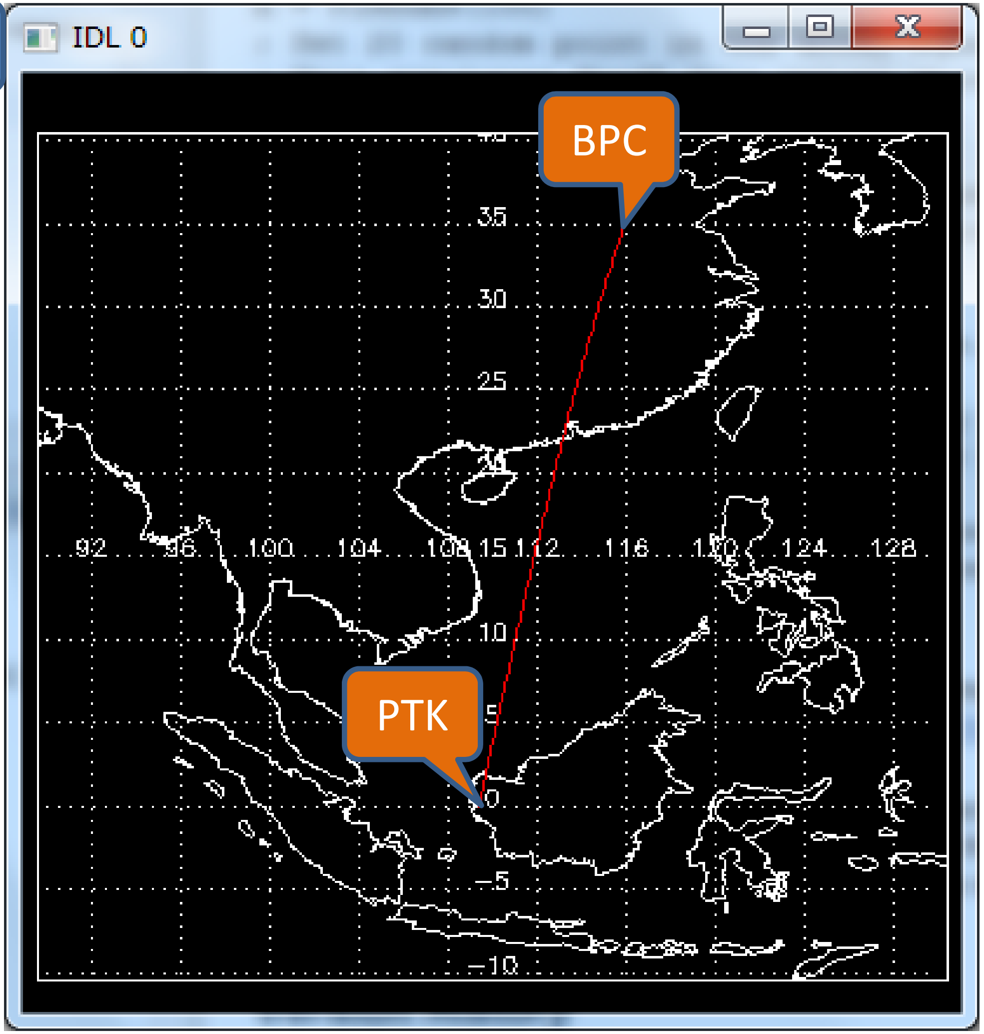
- Overplot the great circle path on the map

```
IDL> oplot, lon, lat, color=240
```

Result 1

Radio propagation path from BPC 68.5kHz transmitter to Pontianak (PTK)

Result 1



(2/5) Reading BPC 68.5kHz phase data measured at Pontianak

- Data format version for PTK is Ver.2.0 (See Appendix B)
- Reading BPC phase data measured at PTK on Jul. 11 2012 UT5:00

```
IDL> dir='C:¥AVON¥LF¥ver2¥'
IDL> date='2012071105'
IDL> read_lfdata, dir=dir, date=date, rx='ptk',
        tx_fq_read=[40.0,60.0,68.5], lf_time=lft, lf_pha=lfp
```

Time and BPC phase records are output to 'lft' and 'lfp[2,*]', respectively.
Phase data of JJY40kHz and 60kHz are also output to lfp[0,*]' and lfp[1,*]'.

- Plot data

```
IDL> window, 1, xsize=600, ysize=400
IDL> plot, lft/3600, lfp[2,*], psym=3,xtitle='Time [UT]',
        ytitle='Phase [degree]'
```

Result 2

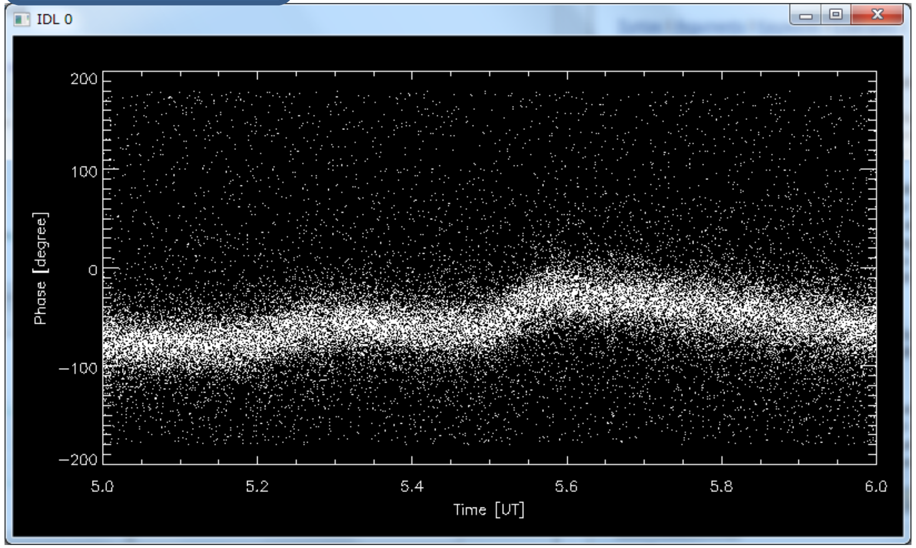
(3/5) Plot the BPC phase data after noise filtering

- Noise filtering (median filter, 100points=10sec)

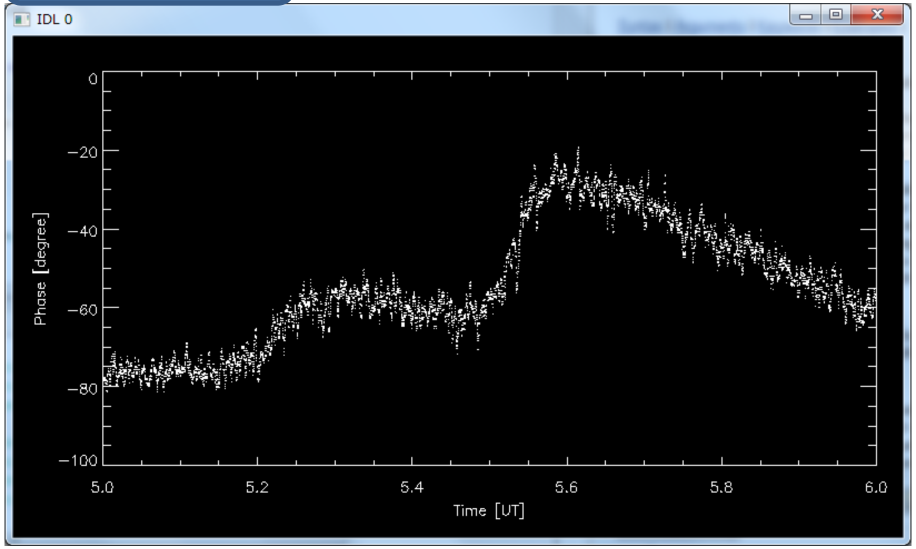
```
IDL> lf_filter, data_in=lfp[2,*], width=100, data_out=flt_out, /set_median
IDL> window, 2, xsize=600, ysize=400
IDL> plot, lft/3600, flt_out, psym=3, xtitle='Time [UT]', ytitle='Phase [degree]'
```

Result 3

Result 2



Result 3



BPC68.5kHz phase change from UT 5-6 on Jul. 11 2012 (raw data, time resolution=0.1sec)

The same as left figure, but median filter whose window size is 100-point (10-eec) is applied.

(4/5) Obtaining and reading GOES15 X-ray flux data

- Open netCDF(one of scientific data formats) data file

```
IDL> file_x = 'C:¥AVON¥LF¥goes¥g15_xrs_2s_20120711_20120711.nc'
```

- Get file ID and variable IDs

```
IDL> id = ncdf_open(file_x)
IDL> id_time = ncdf_varid(id,'time_tag')
IDL> id_a    = ncdf_varid(id,'A_FLUX')
IDL> id_b    = ncdf_varid(id,'B_FLUX')
```

- Get milliseconds since 1970-01-01 00:00:00.0 UTC

```
IDL> ncdf_varget, id, id_time, time_tag
```

- Get XRS short wavelength channel irradiance (0.05 - 0.4 nm) [W/m^2]

```
IDL> ncdf_varget, id, id_a, a_flux
```

- Get XRS long wavelength channel irradiance (0.1-0.8 nm) [W/m^2]

```
IDL> ncdf_varget, id, id_b, b_flux
```

- Close netCDF file

```
IDL> ncdf_close, id
```

(5/5) Compare the transmitter data with the x-ray flux

- Set window

```
IDL> window, 3, xsize=500, ysize=700
IDL> xrange = [5.0,6.0]
IDL>  yrange = [1d-8,5e-6]
IDL> !x.style=1 & !x.ticklen = 1 & !x.gridstyle = 1 & !y.style=1
```

- Plot X-ray data in the upper panel

```
IDL> pos = [0.3,0.5,0.9,0.9]
IDL> hour = (time_tag / 1000.0 / 3600.0) mod 24.0
IDL> plot, hour, a_flux, ytitle='X-ray flux [W/m^2]', pos=pos,
                xrange=xrange, yrange=yrange, /ylog, /nodata
IDL> oplot, hour, a_flux,color=cgColor("Blue")
IDL> oplot, hour, b_flux, color=cgColor("Red")
```

- Plot transmitter data in the bottom panel

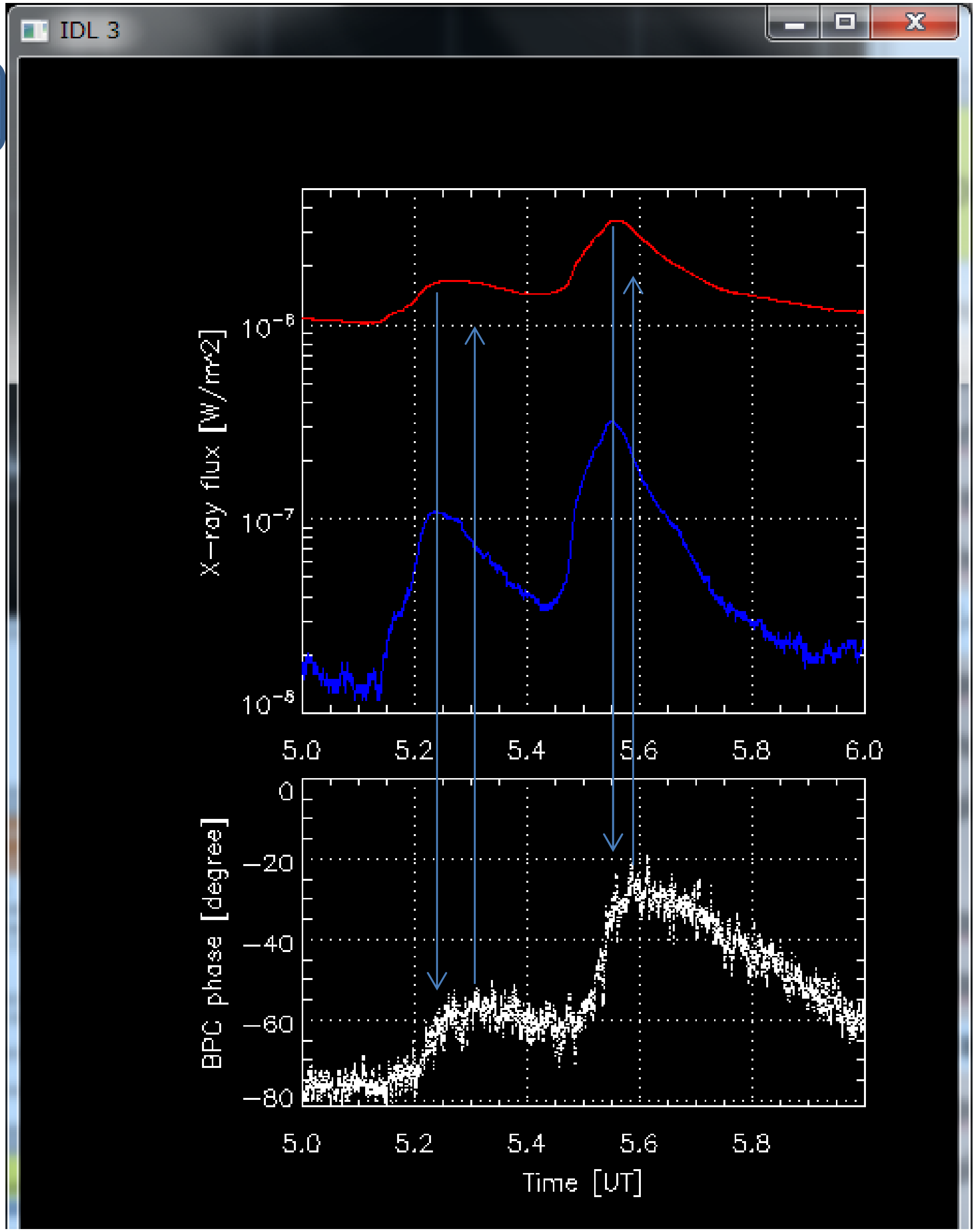
```
IDL> pos = [0.3,0.2,0.9,0.45]
IDL> plot, lft/3600, flt_out, psym=3, xtitle=‘Time [UT]’,
                ytitle=‘BPC phase [degree]’, pos=pos, /noerase
```

Result 4

Compare the transmitter data with the x-ray flux

Result 4

- Comparison between solar X-ray flux (top) and phase change of BPC signal (bottom). It is interesting to note that peaks in the X-ray fluxes advanced those in the phase changes.
- This time difference comes from time constant of electron attachment and/or recombination reactions in the upper atmosphere.



Practical training
[2-2] Data analysis/Early event

- Target : Early event (lightning effect)
- Data source : AVON Tainan and Rikubetsu station
- Other data source : WWLLN (lightning location database)
- Date/Time: Sep 3, 2009, 16UT (Sep. 4, 00JST) & Nov 26, 2013, 16UT
- Overview of data analysis

  Case-1

  - Reading JJY 60kHz data measured at Tainan station
  - Plot the 60kHz phase data after noise filtering

  Case-2

  - Reading JJY 60kHz data measured at Rikubetsu station
  - Plot the 60kHz phase data
  - Check lightning location at the time of the early event

Case 1 (1/3)
Reading JJY 60kHz data measured at Tainan station

Command list : C:¥AVON¥IDL¥log¥ training_2_1.pro

- On Sep. 3 2009, version of data format at Tainan station is Ver.1.0 and time recorded is LT (local time). (See Appendix B)
- Reading JJY and BPC data measured at Tainan on Sep. 4 2009 00:00-1:00 JST

```
IDL> dir='C:¥AVON¥LF¥ver1¥'
IDL> date='2009090400'
IDL> read_lfdata_v1, dir=dir, date=date, rx='twn', /time_corr,
          tx_fq_read=[40.0,60.0,68.5], lf_time=lft,
          lf_amp=lfa, lf_pha=lfp, jjy_code=jjy_code, /lf_sver0
```

- If 'time_corr' keyword is set, 'read_lfdata_v1' analyzes time code derived from JJY40kHz or 60kHz data and corrects time record from JST to UT. JJY time code is also output as 'jjy_code'.
- Time and JJY60kHz phase records are output to 'lft' and 'lfp[1,*]', respectively. (Phase data of JJY40kHz and BPC are 'lfp[0,*]' and 'lfp[2,*]')

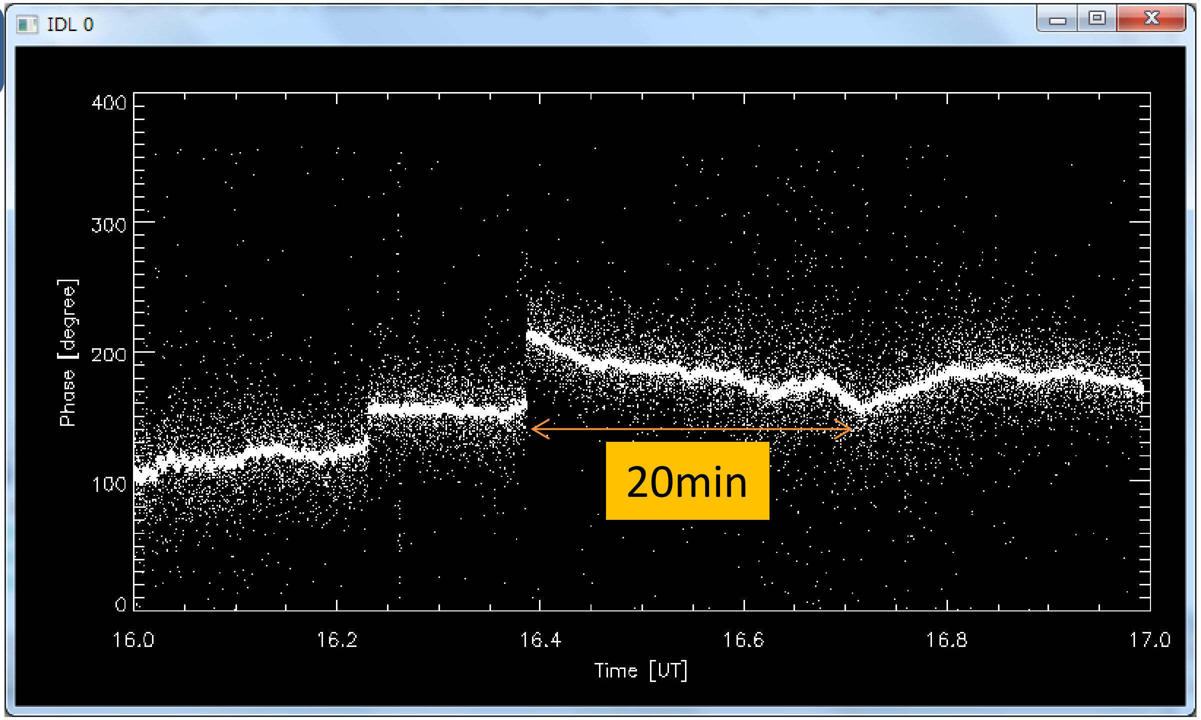
Case 1 (2/3)
Plot the 60kHz phase data

- Plot JJY60kHz phase data

```
IDL> window, 0
IDL>!x.style=1
IDL>plot, lft/3600, lfp[1,*], psym=3, xrange=[16,17],
        xtitle='Time [UT]', ytitle='Phase [degree]’
```

Result 5

Result 5



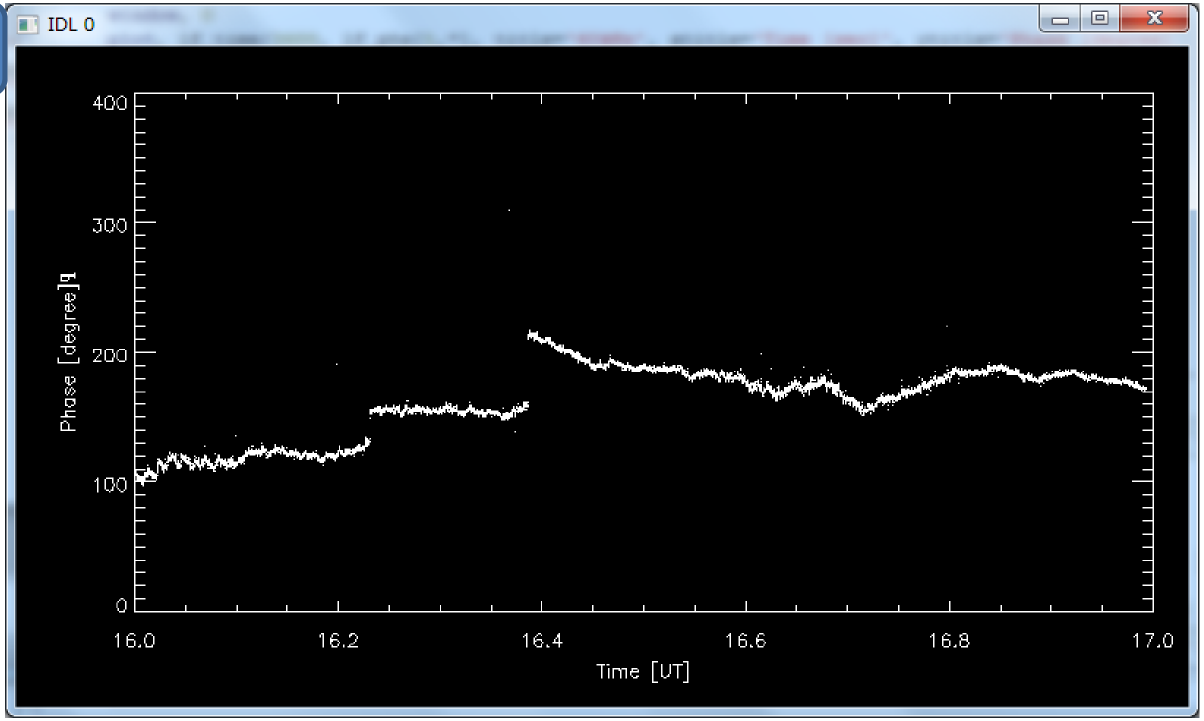
Case 1 (3/3)
Plot the 60kHz phase data after noise filtering

- Plot JJY60kHz phase data

```
IDL> window, 1
IDL> lf_filter, data_in=lfp[1,*], width=10, mask=jjy_code,
          data_out=flt_out, /set_median
IDL>plot, lft/3600, flt_out, psym=3, xrange=[16,17],
          xtitle='Time [UT]', ytitle='Phase [degree]'
```

Result 6

Result 6



Case 2 (1/4)
Reading JJY 60kHz data measured at Rikubstsu station

Command list : C:¥AVON¥IDL¥log¥ training_2_2.pro

- On Nov. 24 2013, version of data format at Rikubetsu station is Ver.1.1 and time recorded is UT(Universal time). (See Appendix B)
- Reading JJY and BPC data

```
IDL> dir='C:¥AVON¥LF¥ver1¥'
IDL> date='2013112616'
IDL> read_lfdata_v1, dir=dir, date=date, rx='rkb', /time_corr,
        tx_fq_read=[40.0,60.0,68.5], lf_time=lft,
        lf_amp=lfa, lf_pha=lfp, jjy_code=jjy_code
```

- Do not set 'lf_sver0' keyword of you will read Ver1.1 data.

Case 2 (2/4)
Plot the 60kHz phase data

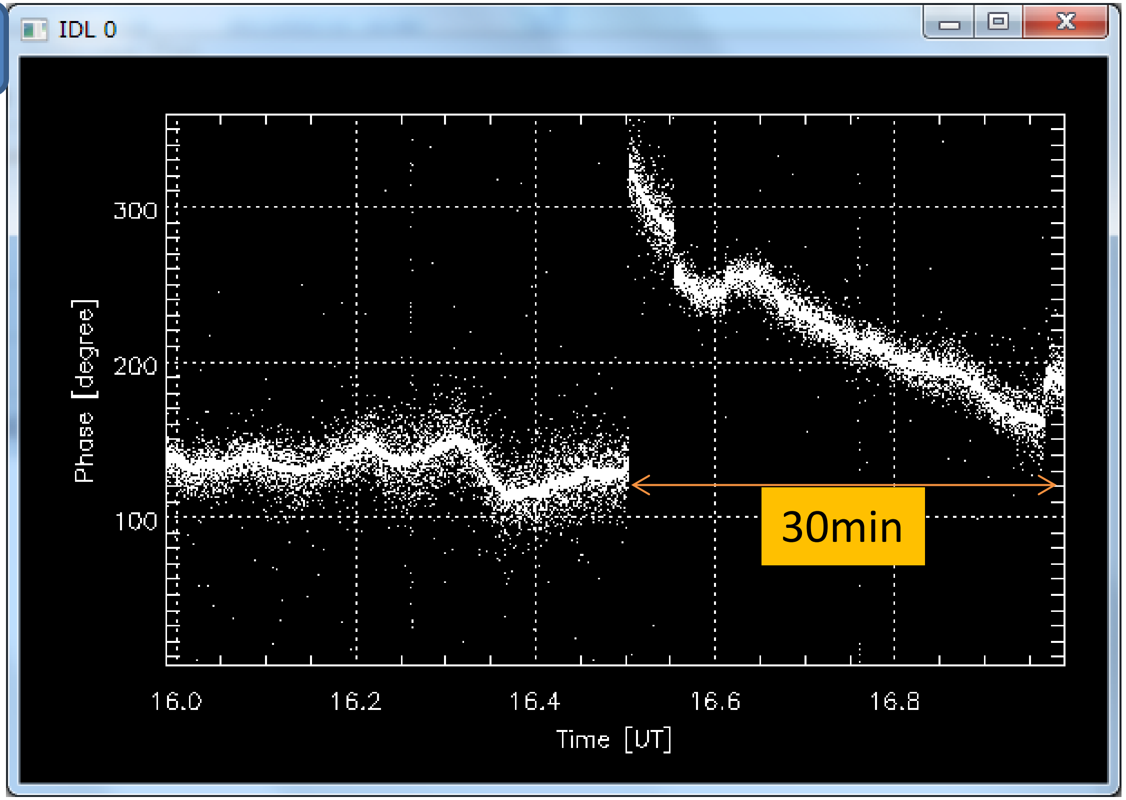
- Plot JJY60kHz phase data

```
IDL> window, 0, xsize=600, ysize=400
IDL>plot, lft/3600, lfp[1,*], psym=3, xtitle='Time [UT]',
        ytitle='Phase [degree]'
```

Result 7

Result 7

Detection of "early Trimpi event" with very long recovery. Phase jump around 16:30UT may be caused by lightning induced localized ionization in the lower ionosphere.



Case 2 (3/4)
Check JJY time code and time correction

- Plot JJY time code

```
IDL>  window, 1, xsize=800, ysize=300
IDL>  xrange = [16.496,16.505]
IDL> plot, lft/3600, jjy_code, xtitle='Time [UT]',
          ytitle='Time code', xrange= xrange, yr=[-0.5,1.5]
```

Result 7

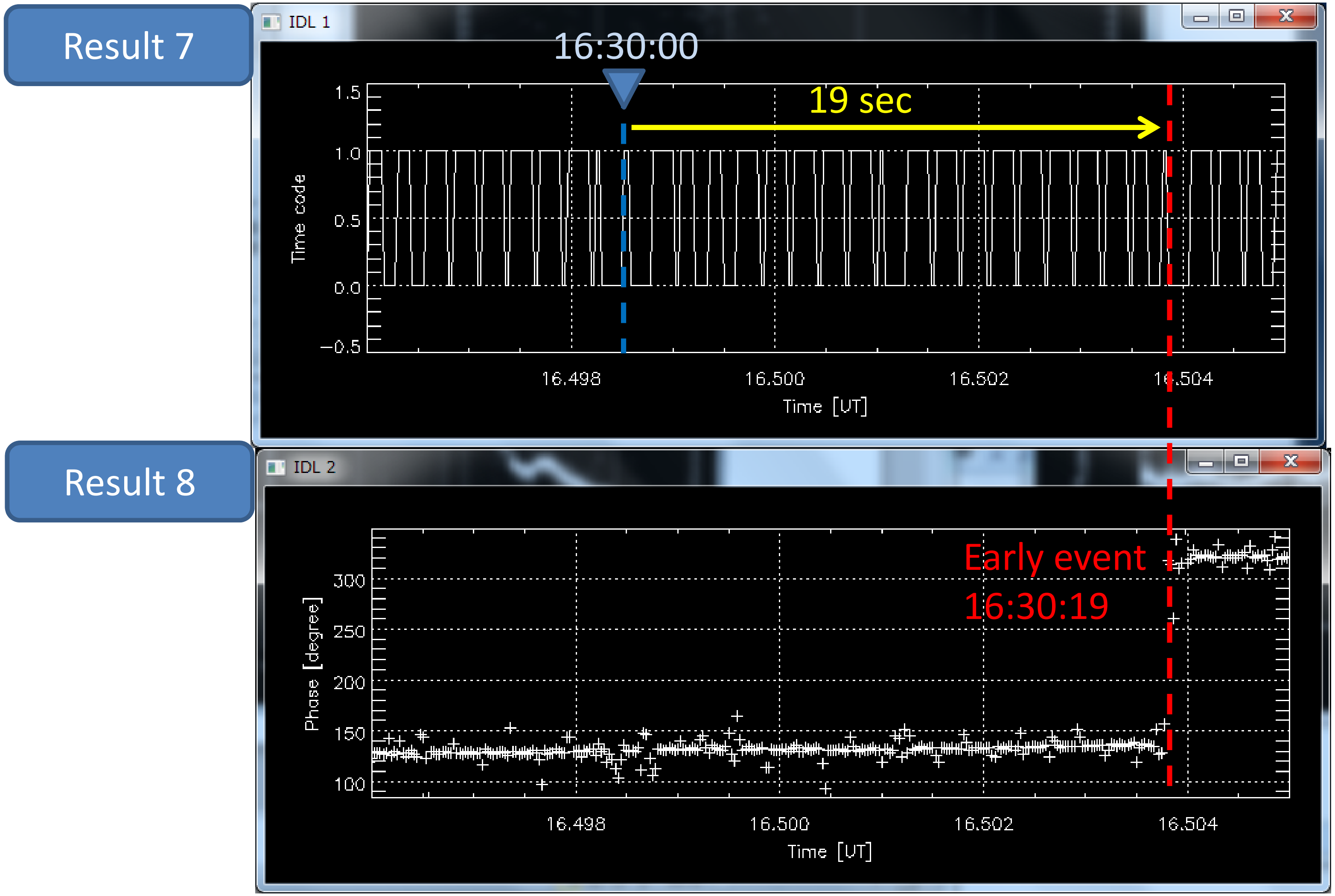
- Plot JJY60kHz phase data

```
IDL>  window, 2, xsize=800, ysize=300
IDL> plot, lft/3600, lfp[1,*], psym=1,xtitle='Time [UT]',
          ytitle='Phase [degree]', xrange=xrange
```

Result 8

Check JJY time code and time correction

JJY time code derived from JJY60kHz data (see Appendix D)



Phase of JJY60kHz signal

Case 2 (4/4)
Find causative lightning with WWLLN*

- Location of JJY60kHz transmitter (src) and Rikubetsu station (trg)

```
IDL> src=[130.18,33.47] & trg = [143.77,43.45]
```

- Calculation of GCP between source to target

```
IDL> lf_get_gcp, src=src, trg=trg, gcp_lon=lon, gcp_lat=lat
```

- Date and time range

```
IDL> date = ‘20131126'
IDL> stime = '16:30:19.000‘ & etime = '16:30:20.000'
```

- Find WWLLN data

```
IDL>dir = 'C:¥AVON¥LF¥wwlln¥'
IDL> lf_get_wwlln, dir=dir, date=date, sta_time=stime,
         end_time=etime, ltime=ltime, llon=llon, llat=llat
```

- Set window size

```
IDL> window, 3, xsize=500, ysize=500
```

---

*WWLLN data is distributed from Washington University.
Contact person is Prof. Holzworth (http://wwlln.net/new/)

Find causative lightning with WWLLN

- Plot map

```
IDL> map_set, limit=[25.0,120.0,50.0,150.0], /cylindrical
IDL> map_grid, /label
IDL> map_continents,/continents
```

- Overplot Great Circle path

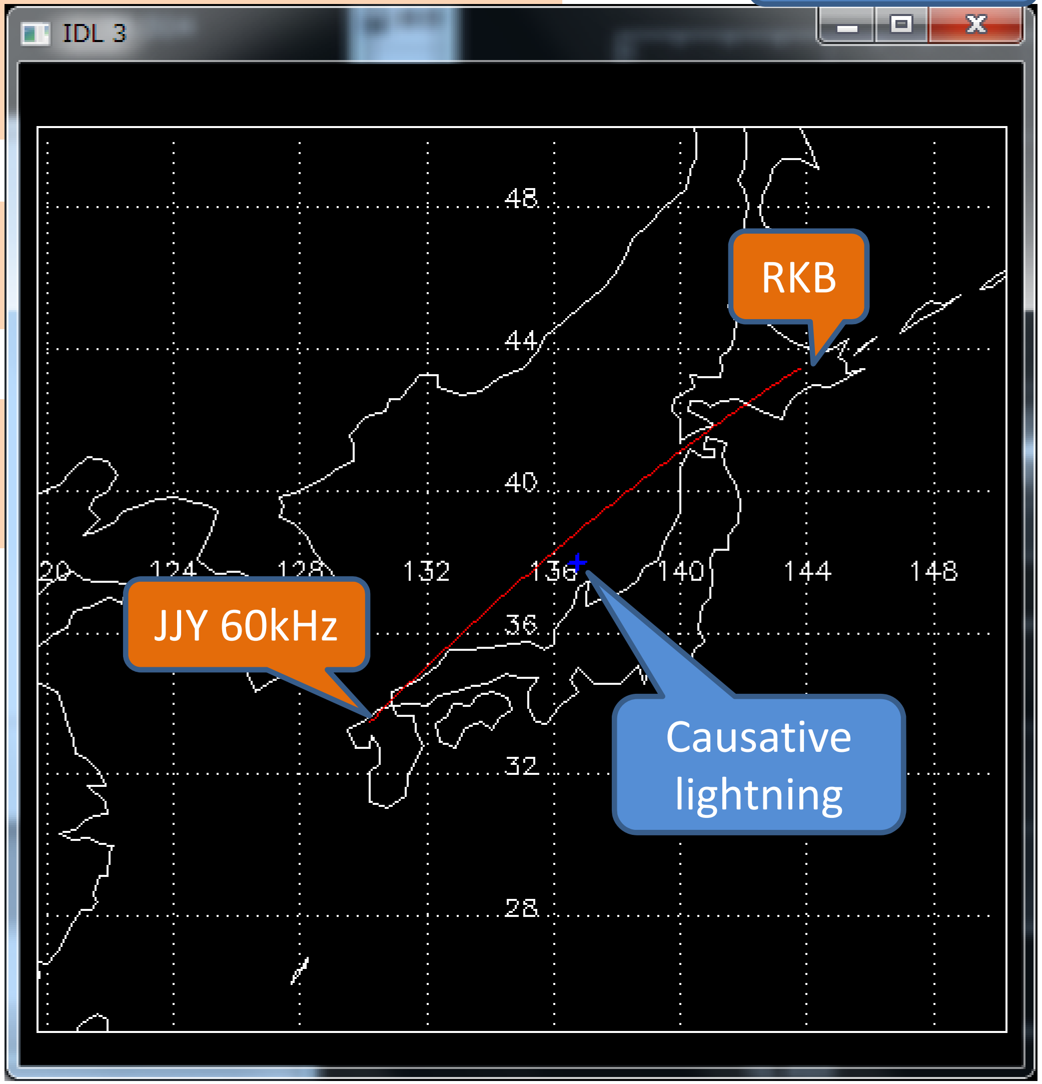
```
IDL> oplot, lon, lat,
        color=cgColor("Red")
```

- Overplot WWLLN data

```
IDL>oplot, llon, llat, psym=1,
        color=cgColor("Blue")
```

Result 9

Result 9



Acknowledgments

RX station		
ATH	Athabasca/Canada	Dr. Martin Connors, Athabasca University
NYA	Ny-Alseund/Norway	National Institute of Polar Research, Japan The Norwegian Polar Institute
PKR	Polar Flat/AK USA	Dr. Donald Hampton, University of Alaska, Fairbanks
PTK	Pontianak/Indonesia	Dr. Timbul Manik, LAPAN
RKB	Rikubetsu/Japan	Drs. Shiokawa and Miyoshi, Nagoya University Mr. Yokozeki, Rikubetsu observatory
SGR	Sasaguri/Japan	Drs. Yoshikawa, Abe, and Uozumi, Kyushu University
SRB	Saraburi/Thailand	Prof. Thanawat Jarupongsakul and Mr. Vijak Pangsapa, Chulalongkorn University Dr. Boossarasiri Thana , Promotion of Teaching Science and Technology (IPST)
TKN	Takine/Japan	Mr. Ohno, Hoshi-no-mura astronomical observatory
TWN	Tainann/ROC	Dr. Alfred Chen, NCKU
ZAO	Zao/Japan	Zao observatory, Tohoku University

Appendix A: Data format
Ver.1.0

- File name: rrrYYYYMMDDHH.dat.0.gz (rrr: station name)
- Format gzipped-ascii file
  - 1st column: amplitude of received signal at 40.0kHz
  - 2nd column: phase of received signal at 40.0kHz
  - 3rd column: amplitude of received signal at 60.0kHz
  - 4th column: phase of received signal at 60.0kHz
  - 5th column: amplitude of received signal at 19.8kHz
  - 6th column: phase of received signal at 19.8kHz
  - 7thcolumn: amplitude of received signal at 21.4kHz
  - 8th column: phase of received signal at 21.4kHz
  - 9th column: amplitude of received signal at 22.2kHz
  - 10th column: phase of received signal at 22.2kHz
  - 11th column: amplitude of received signal at 24.8kHz
  - 12th column: phase of received signal at 24.8kHz
  - 13th column: amplitude of received signal at 25.0kHz
  - 14th column: phase of received signal at 25.0kHz
  - 15th column: amplitude of received signal at 50.0kHz
  - 16th column: phase of received signal at 50.0kHz
  - 17th column: amplitude of received signal at 54.0kHz
  - 18th column: phase of received signal at 54.0kHz
  - 19th column: amplitude of received signal at 68.5kHz
  - 20th column: phase of received signal at 68.5kHz
- Time resolution : 0.1sec

Ver.1.1

- File name: rrrYYYYMMDDHH.dat.gz (rrr: station name)
- Format gzipped-ascii file
  - 1st column: second of hour
  - 2nd column: amplitude of received signal at 40.0kHz
  - 3rd column: phase of received signal at 40.0kHz
  - 4thcolumn: amplitude of received signal at 60.0kHz
  - 5th column: phase of received signal at 60.0kHz
  - 6th column: amplitude of received signal at 19.8kHz
  - 7th column: phase of received signal at 19.8kHz
  - 8thcolumn: amplitude of received signal at 21.4kHz
  - 9th column: phase of received signal at 21.4kHz
  - 10th column: amplitude of received signal at 22.2kHz
  - 11th column: phase of received signal at 22.2kHz
  - 12th column: amplitude of received signal at 24.8kHz
  - 13th column: phase of received signal at 24.8kHz
  - 14th column: amplitude of received signal at 25.0kHz
  - 15th column: phase of received signal at 25.0kHz
  - 16th column: amplitude of received signal at 50.0kHz
  - 17th column: phase of received signal at 50.0kHz
  - 18th column: amplitude of received signal at 54.0kHz
  - 19th column: phase of received signal at 54.0kHz
  - 20th column: amplitude of received signal at 68.5kHz
  - 21st column: phase of received signal at 68.5kHz
- Time resolution : 0.1sec

Ver.2.0

- File name: RRRYYYYMMDDHH.dat.gz (RRR: station name)
- Format binary file
  - 1st block : header block (header block size is the same as data blocks)
  - 2nd block : data block1 : data measured from HH:00:00.0 to HH:00:00.9
  - 3rd block : data block2 : data measured from HH:00:01.0 to HH:00:01.9

    …
  - 3601th block : data block3600: data measured from HH:59:59.0 to HH:59:59.9

  Size of each block : Number of frequency channel x 20 x 2Byte + 4Byte

- Header format
  - Year(YYYY): 2Byte
  - Month/day(MMDD): 2Byte
  - Hour(HH): 2Byte
  - Sampling frequency[kHz]: 2Byte
  - Data length for FFT[point]: 2Byte
  - Number of frequency channel : 2Byte
  - Block size [Byte]: 2Byte
  - Frequencies recorded: 2Byte x Number of frequency channel

Ver.2.0 (continued)

- Data block : block size = Number of frequency channel x 20 x 2Byte + 4Byte
  - Start mark (0xFFFF): signed single (2Byte)
  - Time (mmss) : signed single (2Byte)
  - Amplitude x NF @ HHmmss.0 signed single (2byte) x NF
  - Phasex xNF @ HHmmss.0 signed single (2byte) x NF
  - Amplitude x NF @ HHmmss.1 signed single (2byte) x NF
  - Phase x NF @ HHmmss.1 signed single (2byte) x NF
  - …
  - Amplitude x NF @ HHmmss.9 signed single (2byte) x NF
  - Phase x NF @ HHmmss.9 signed single (2byte) x NF

  *NF : Number of frequency channel

- Time resolution : 0.1sec

Appendix B: List of Receivers(1/2)

	Location	Latitude [degree]	Longitude [degree]	Antenna *1	Data format (See appendix A)
ATH	Athabasca /Canada	54.7	246.7	LF4060	Ver2.0(2010-10-24 -)
NYA	Ny-Alseund /Norway	78.933	11.867	LF4060	Ver2.0(2010-03-07 -)
PKR	Polar Flat /AK USA	65.125	212.512	DX one Pro mkII	Ver2.0(2014-10-17 -)
PTK	Pontianak /Indonesia	00.003	109.367	LF4060	Ver2.0(2010-08-26 -)
RKB *2	Rikubetsu /Japan	43.45	143.77	LF4060	Ver1.0(2006-03-08 to 2010-04-24) Ver1.1(2010-04-28 to 2015-03-15*3) Ver2.0(2015-03-15 - *3)
SGR	Sasaguri/ Japan	33.632	130.505	LFL1010	Ver2.0(2014-11-27 -)

*1 LF4060/DX one Pro mkII (Vertical electric antennas): RF systems
LFL1010 (magnetic loop antenna): Wellbrook Communications

*2 In early phase of observation, time recorded was based on LT instead of UT
(until 2010-04-26 for RKB)

*3 planned

Appendix B: List of Receivers(2/2)

	Location	Latitude [degree]	Longitude [degree]	Antenna *1	Data format (See appendix A)
SRB	Saraburi /Thailand	14.528	100.910	LF4060 (2012-06-12 -) DX one Pro mkII (2014-03-09 -)	Ver2.0(2012-06-12 -)
TKN	Takine/ Japan	37.342	140.676	LFL1010	Ver2.0(2014-12-13 -)
TWN *2	Tainann /ROC	23.07	120.12	LF4060 (2007-12-28 -) DX one Pro mkII (2013-03-04 -)	Ver1.0(2007-12-28 to 2010-04-22) Ver1.1(2010-04-27 to 2014-11-15) Ver2.0(2014-12-28 -)
ZAO *2	Zao /Japan	38.10	140.53	DX one Pro mkII	Ver1.0(2007-10-10 to 2010-02-21) Ver2.0(2010-02-21 -)

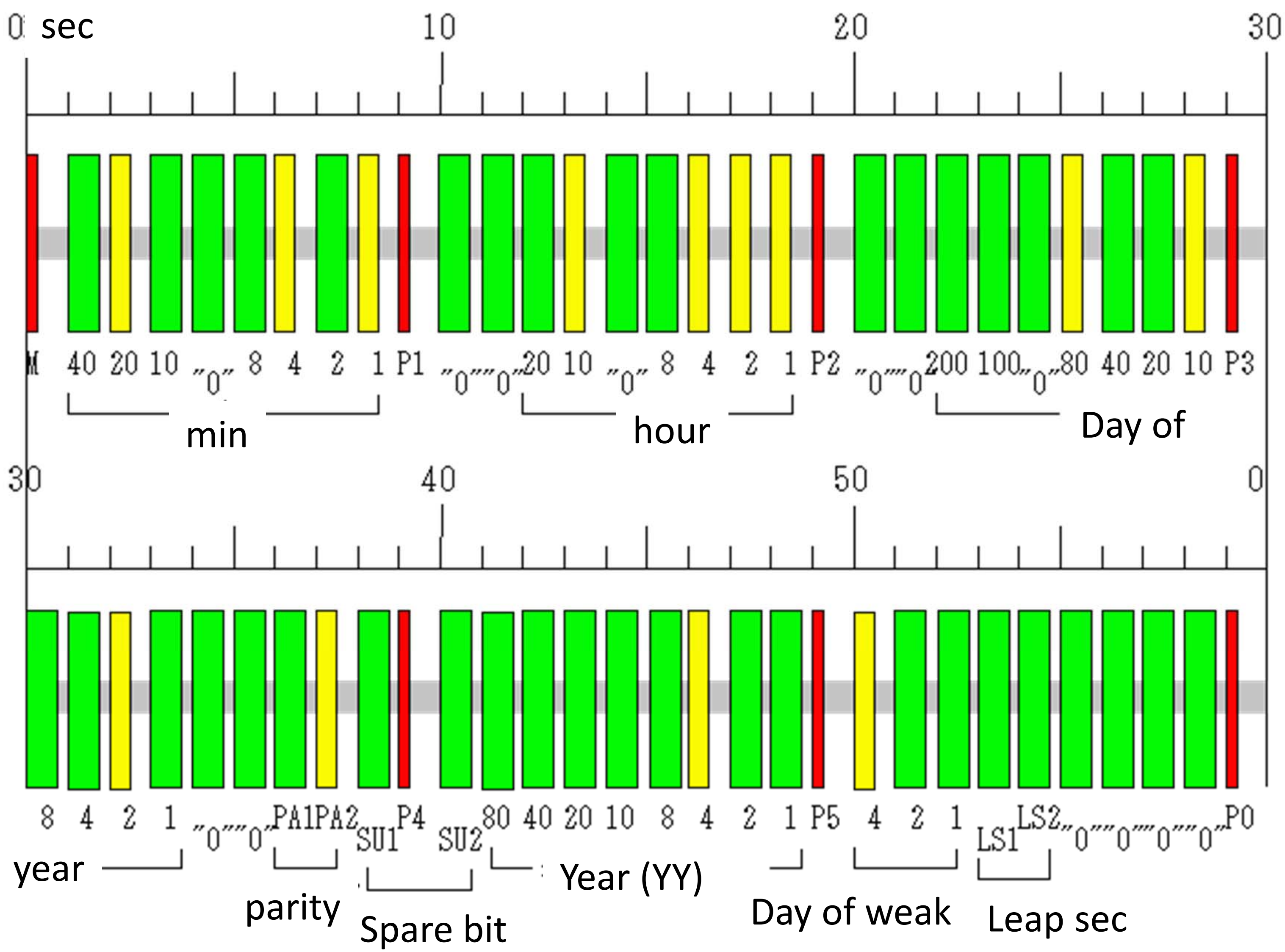
*1 LF4060/DX one Pro mkII (Vertical electric antennas): RF systems
LFL1010 (magnetic loop antenna): Wellbrook Communications

*2 In early phase of observation, time recorded was based on LT instead of UT
(until 2010-04-26 for TWN, and 2010-04-29 for ZAO)

Appendix C: List of major transmitters

Station	Location	Latitude [degree]	Longitude [degree]	Frequency
JJY	Japan	37.37	140.85	40.0kHz
JJY	Japan	33.47	130.18	60.0kHz
BPC	China	34.63	115.83	68.5kHz
JJI	Japan	32.05	130.82	22.2kHz
NWC	Australia	-21.817	114.167	19.8kHz
WWVB	United States	40.667	254.950	60.0kHz
NAA	United States	44.650	292.717	24.0kHz
NDK	United States	46.367	261.467	25.2 kHz
NLK	United States	48.200	238.083	24.8kHz
NPM	United States (Hawaii)	21.000	202.0	21.4kHz
NRK	Iceland	63.9833	-22.6	37.5kHz
MSF	United Kingdom	54.9167	-3.25	60.0kHz
DCF	Germany	50.0156	9.0108	77.5kHz

Appendix D: JJY Time code



Appendix E: IDL functions

- **Load procedure and analysis tools for AVON VLF/LF transmitter radio observation data**
- **See each sample code (*.pro in C:¥AVON¥IDL¥LF) for detail.**
  - **read_lfdata_v1**
    read version 1.0 and 1.1 data
  - **read_lfdata**
    read version 2.0 data
  - **lf_get_gcp**
    get great circle path (GCP) between two points
  - **lf_filter**
    filtering phase/amplitude data (median or smoothing)
  - **lf_get_wwlln**
    get lightning location data from WWLLNN
  - **lf_search_jjy_code**
    search time code in JJY amplitude data (40 or 60kHz)