Range imaging by single pulse FDI - heater induced FAIs observed by SuperDARN and EISCAT

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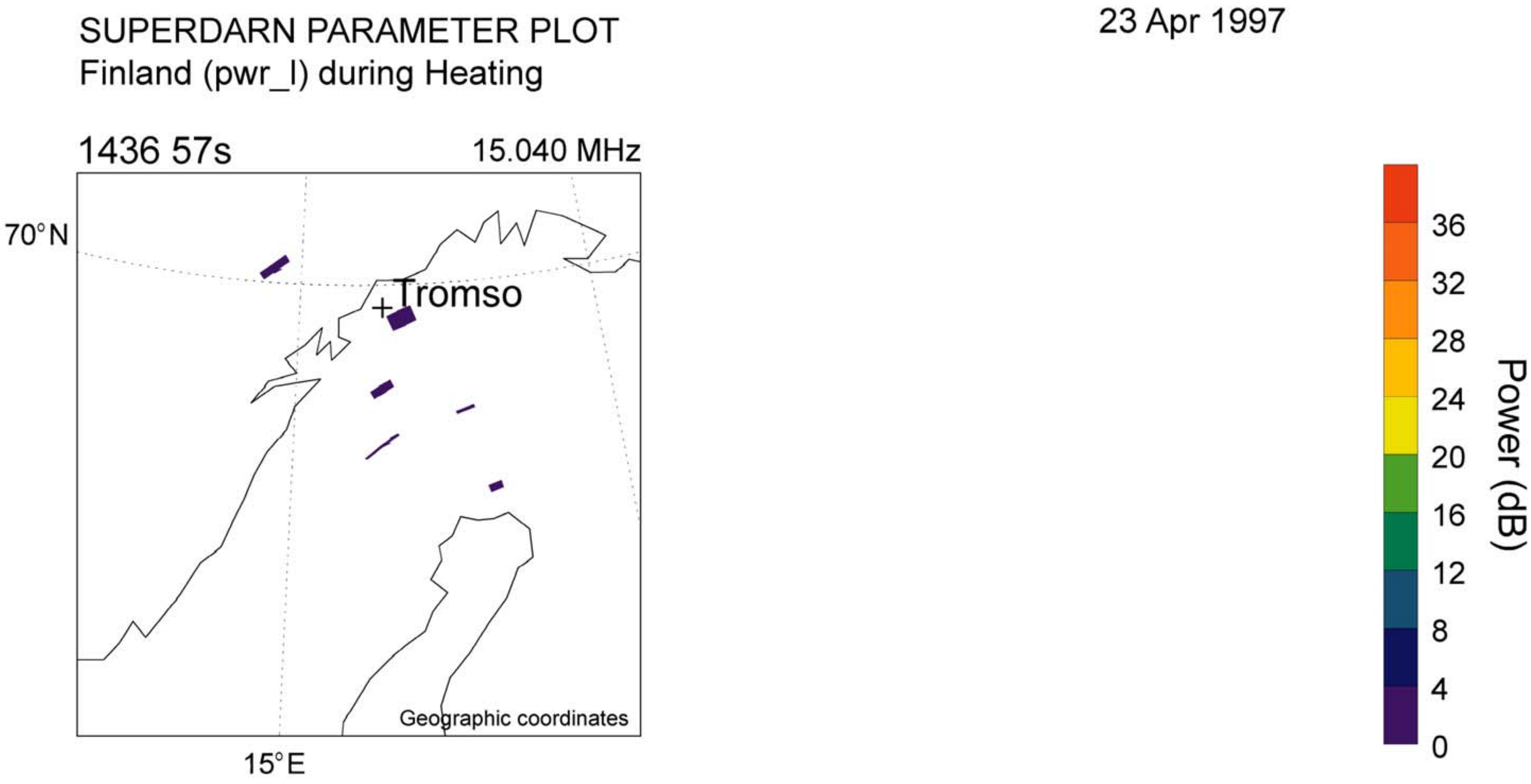
NIPR/ROIS/SOKENDAI, Tokyo, EISCAT Association and Univ. of Leicester, UK

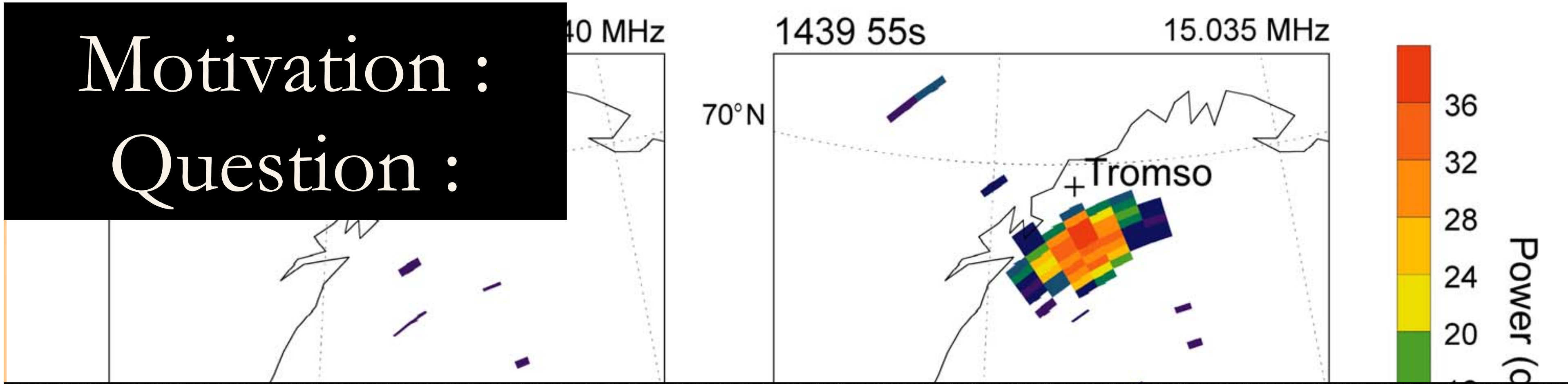
Artificially induced FAIs by EISCAT Tromso heating facility observed with CUTLASS Finland & Iceland East SuperDARN radars and EISCAT Tromso UHF radar



Heater Off

EISCAT data:
http://polaris.nipr.ac.jp/~yogawa/sp_ni_fai/

Motivation :
Question :



Are heater induced FAIs spread over the region just silently and "flatly"? or lots of or some limited number of "soliton-like" FAIs are created and decayed frequently / repeatedly like "bubbles" in boiling water in a kettle? or mixture of them, or something very different? ---- still unknown *(Terry said)*

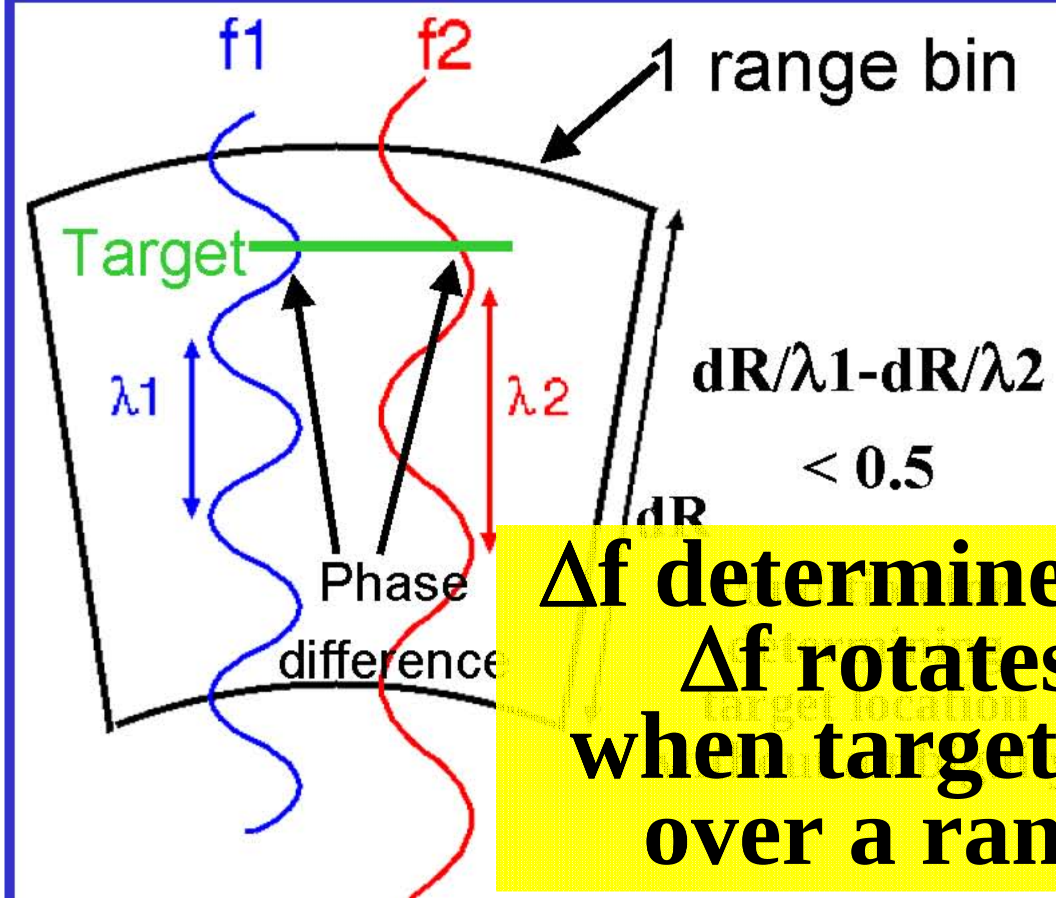
⇒ try to contribute to theory/models

To obtain finer structure of FAI echoes in range direction:

- **oversampling** (for single discrete target)
- **pulse/phase coding**
  (additional radio authority license might required)
- **FDI** with TMS
  (If S/N ratio is enough high, highest resolution might be expected like SDI (angular space imaging).
  & Just additional software, free!)

(Dual freq) FDI
(Frequency Domain Interferometer)

Use **2 closely adjacent freqs** **(Δf~kHz)**
Infer **fine range location within a range cell**
using **phase differences** by **dual freq observation**



freq difference

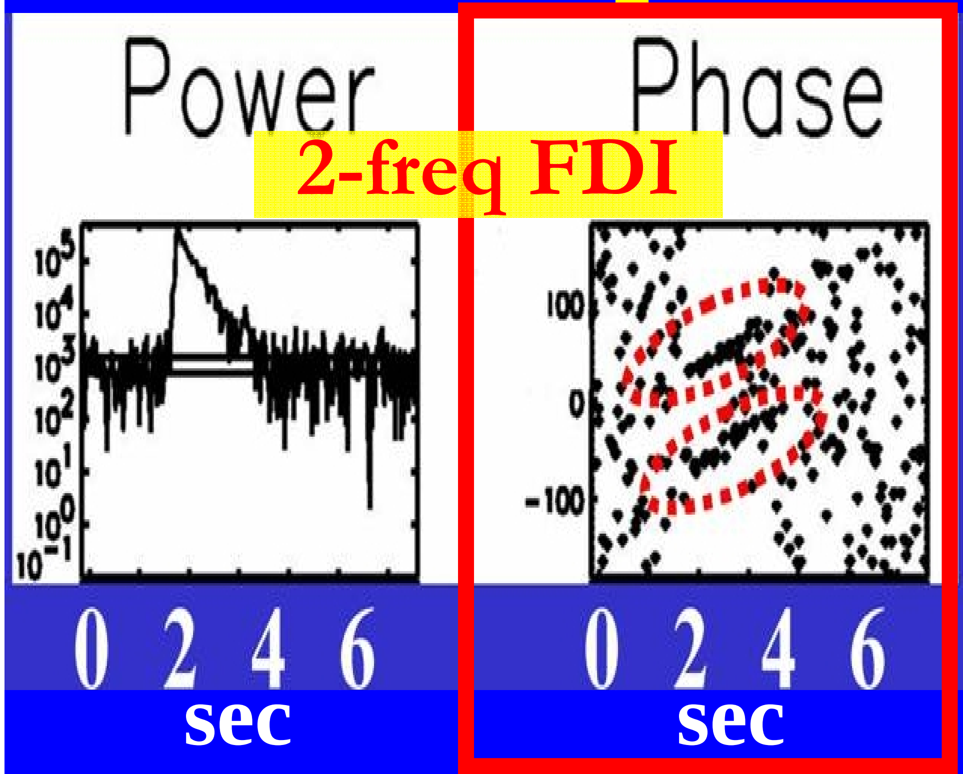
$|\Delta f| < dR/c$

$|\Delta f| < 3.33$ kHz (rsep 45km)
$|\Delta f| < 5.0$ kHz (rsep 30km)
$|\Delta f| < 10$ kHz (rsep 15km)

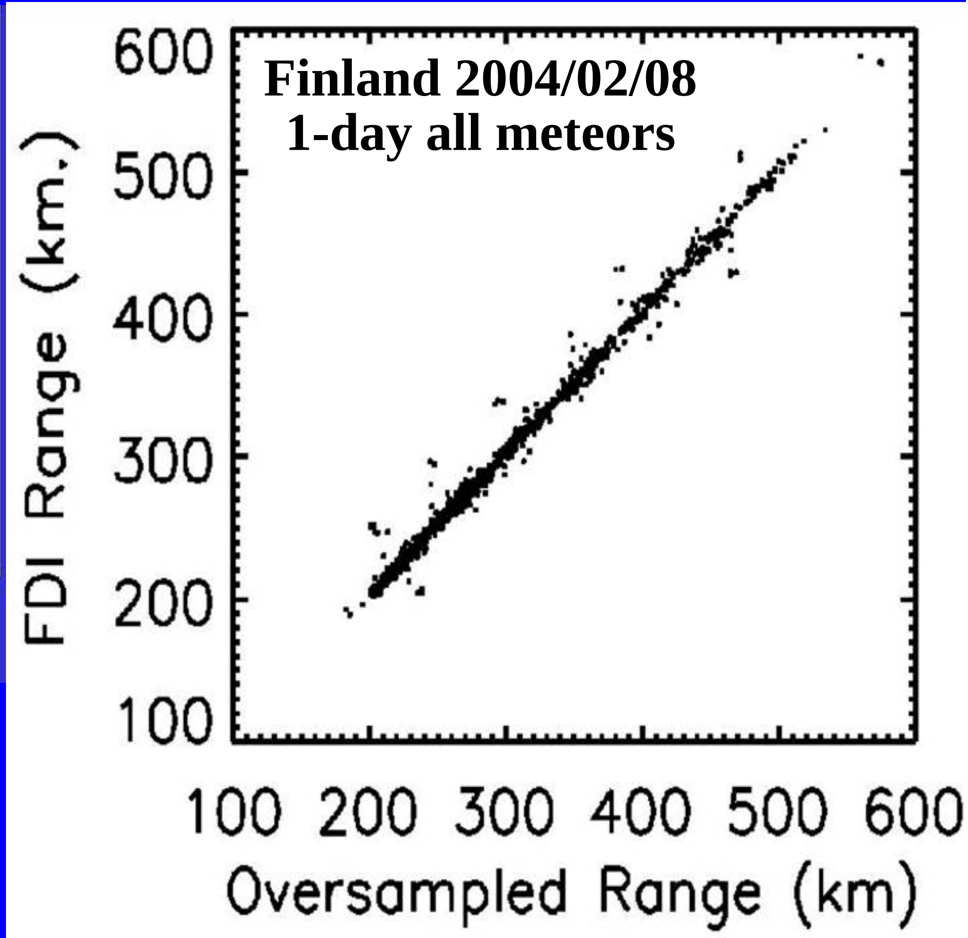
Δf determined so that
Δf rotates < 2π
when targets moved
over a range cell

N frequencies
may resolve
(N-1) targets

High Range Res. Meteor Obs. by Dual Freq FDI (Tutumi et al SD WS 2004)

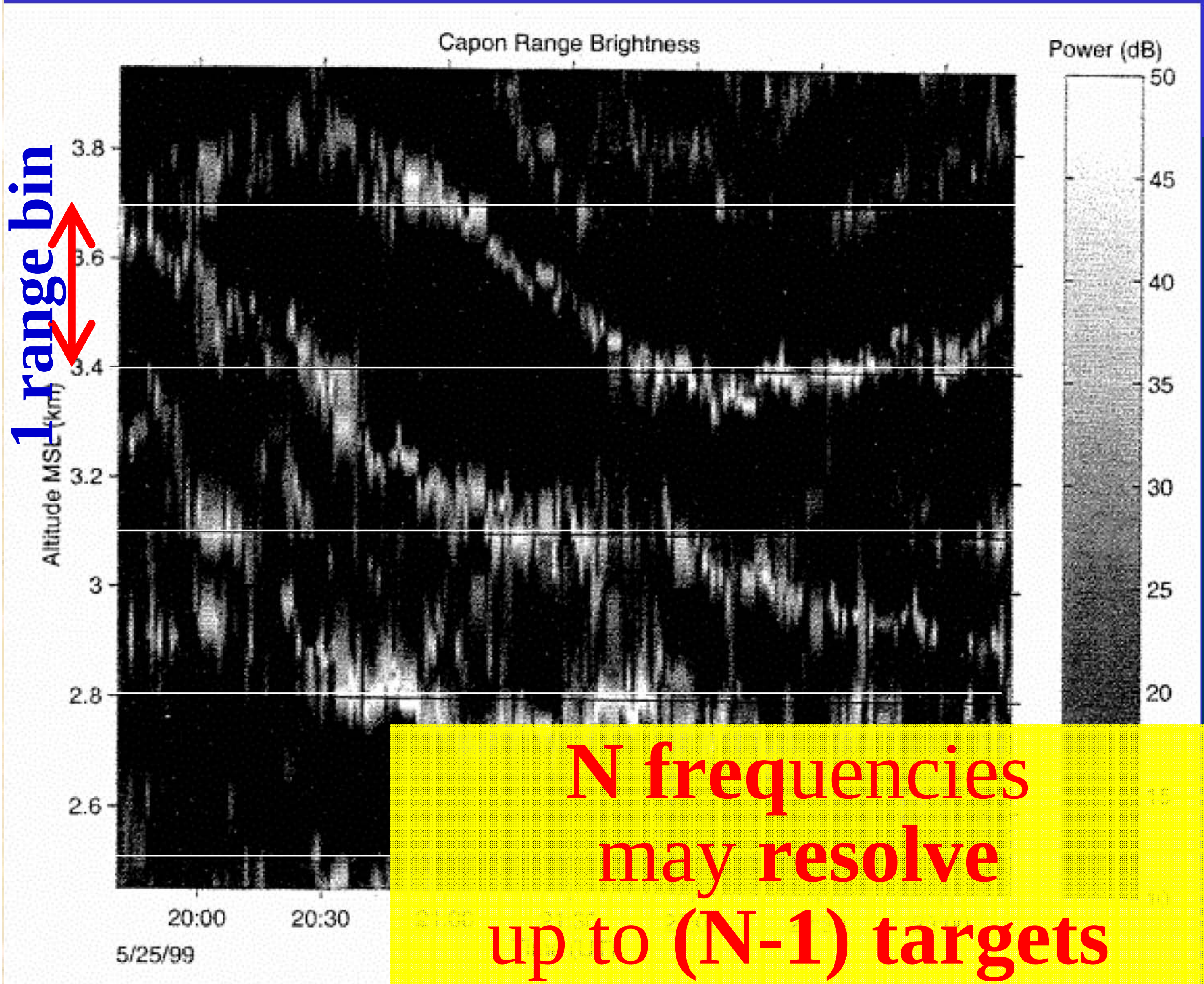


Change TxFreq every pulse sequence (i.e., Tilt TxFreq), 2 phase groups seen



FDI vs Over-Sampling Nice Agreement!

An Example of Multi-freq FDI obs. in case of ST radar stratosphere obs



Palmer et al., Radio Sci, 2001.

4-freq FDI echo Power by ST radar.

original rsep=300m

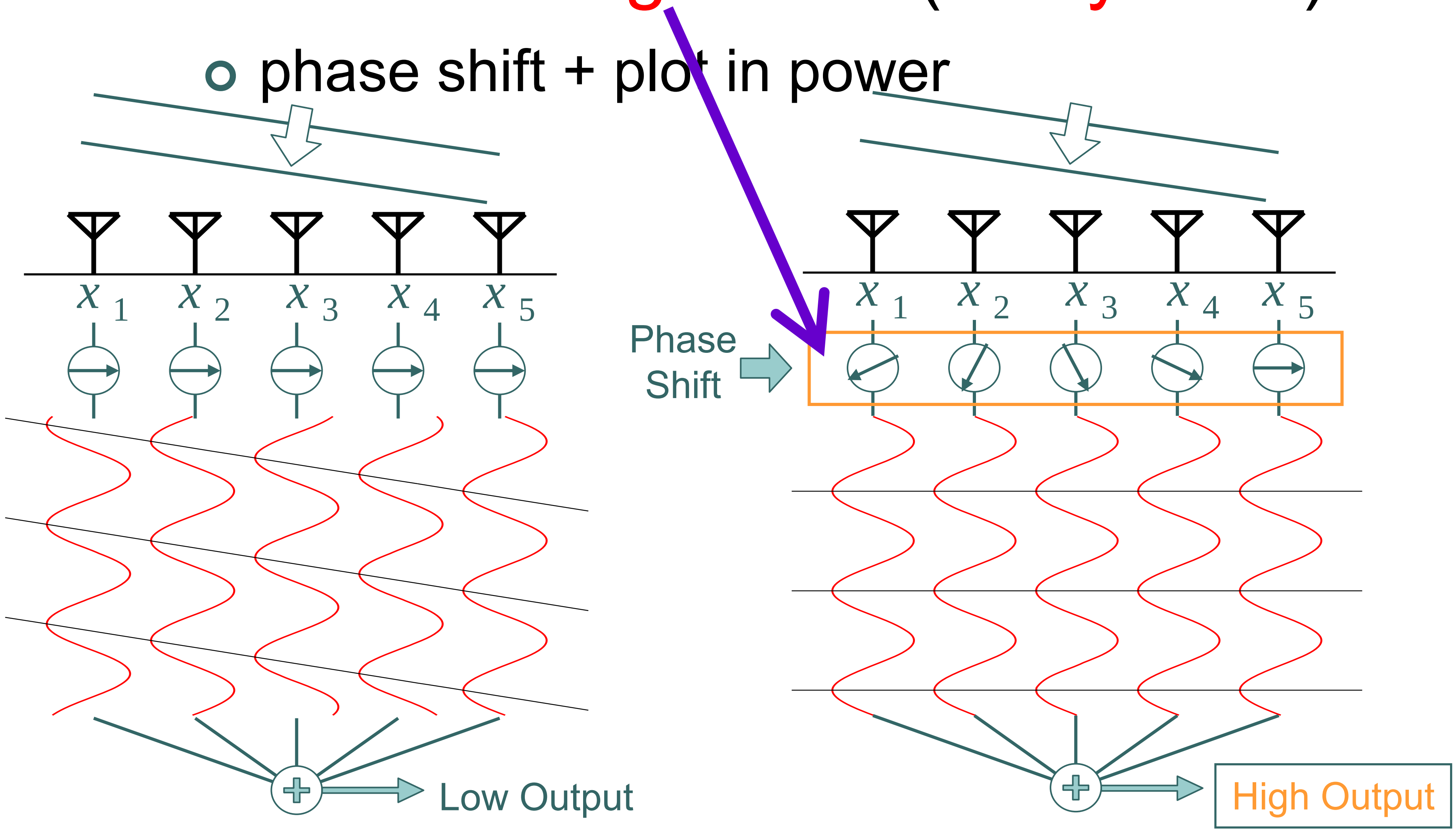
FDI resolved much thinner turbalence layer structures within range cells

N frequencies may **resolve** up to **(N-1) targets**

Spatial Domain Interferometer(beam forming)

Fourier Method (=Conventional beam forming) with Phasing Matrix (delay lines)

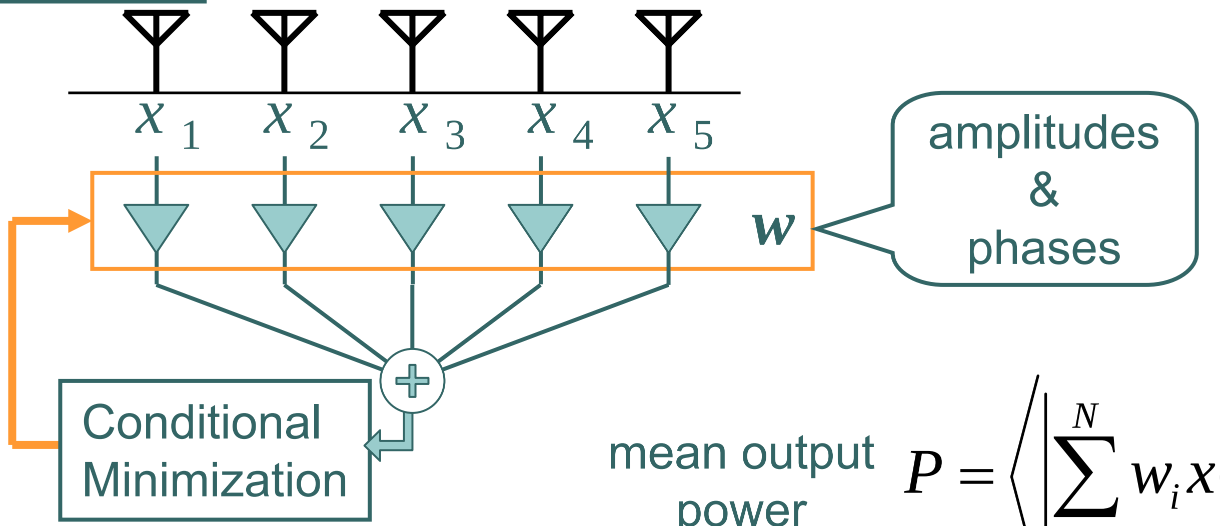
- phase shift + plot in power



Spatial Domain Interferometer(beam forming)

Capon Method (Adaptive beam forming)

System Model



mean output power $P = \left\langle \left| \sum_{i}^{N} w_i x(t) \right|^2 \right\rangle$

Capon's Algorithm

Statement

$$\underset{\mathbf{w}}{\text{minimize}} \left\{ P = \mathbf{w}^{\mathrm{H}} R_{xx} \mathbf{w} \right\}$$

$$\text{subject to } \mathbf{w}^{\mathrm{H}} \mathbf{c} = 1$$

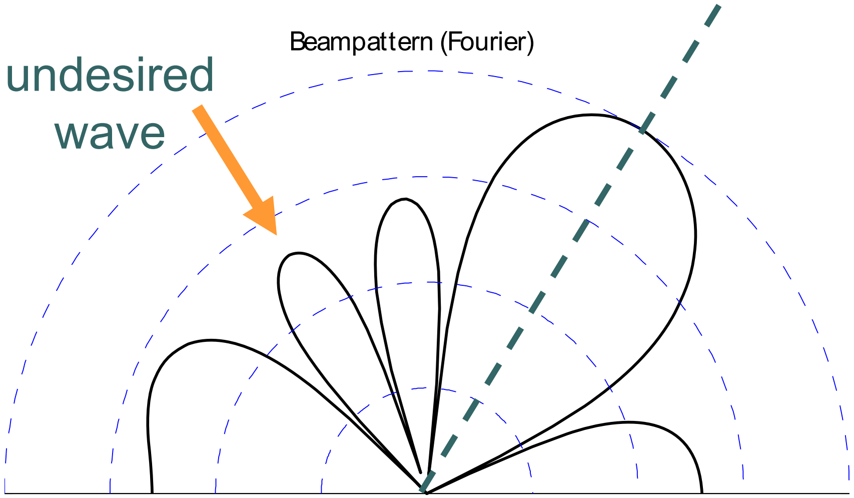
Solution

$$P(\theta) = \frac{1}{\mathbf{c}^{\mathrm{H}} R_{xx}^{-1} \mathbf{c}}$$

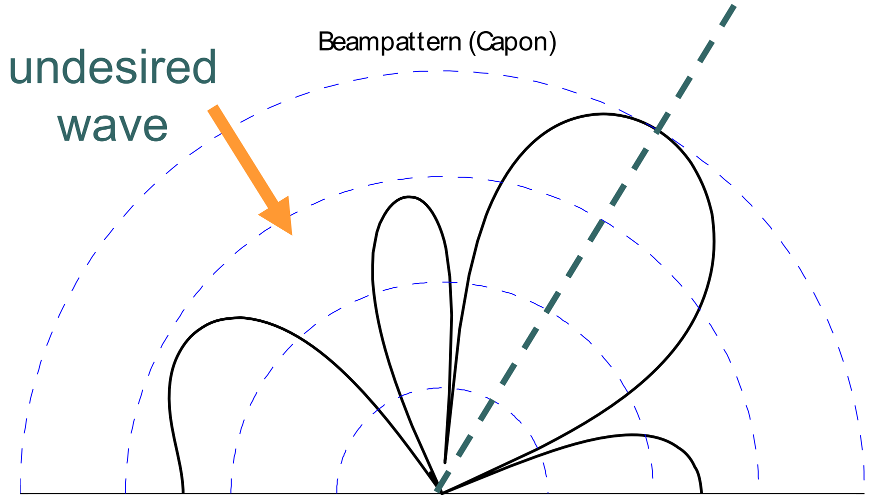
Basic Characteristics of Fourier & Capon Beampattern

- Instantaneous beampatterns

by Fourier Method



by Capon Method



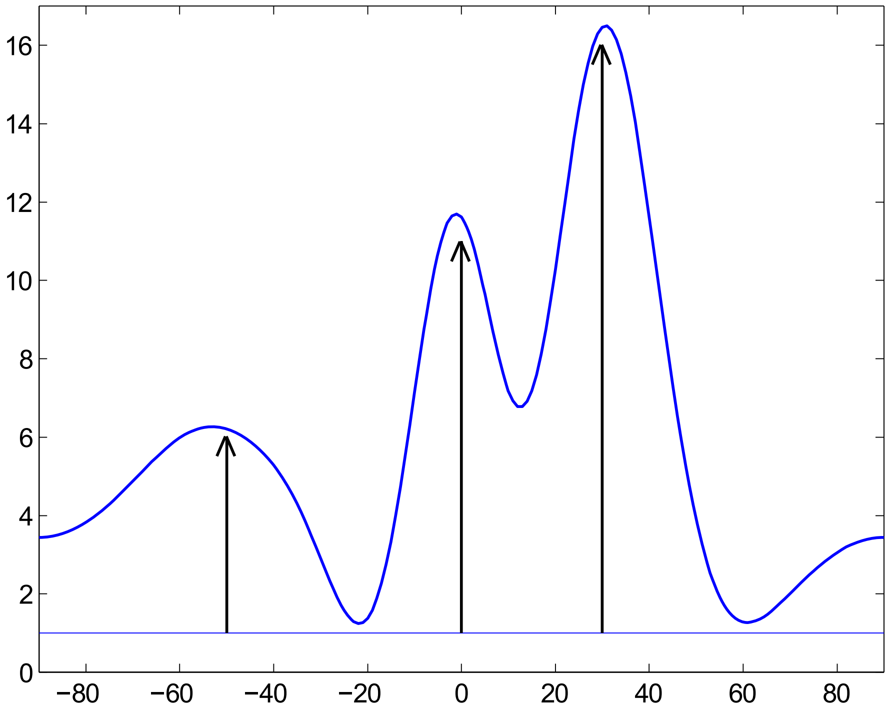
undesired input is cancelled

(This principle is also employed for clutter cancellation)

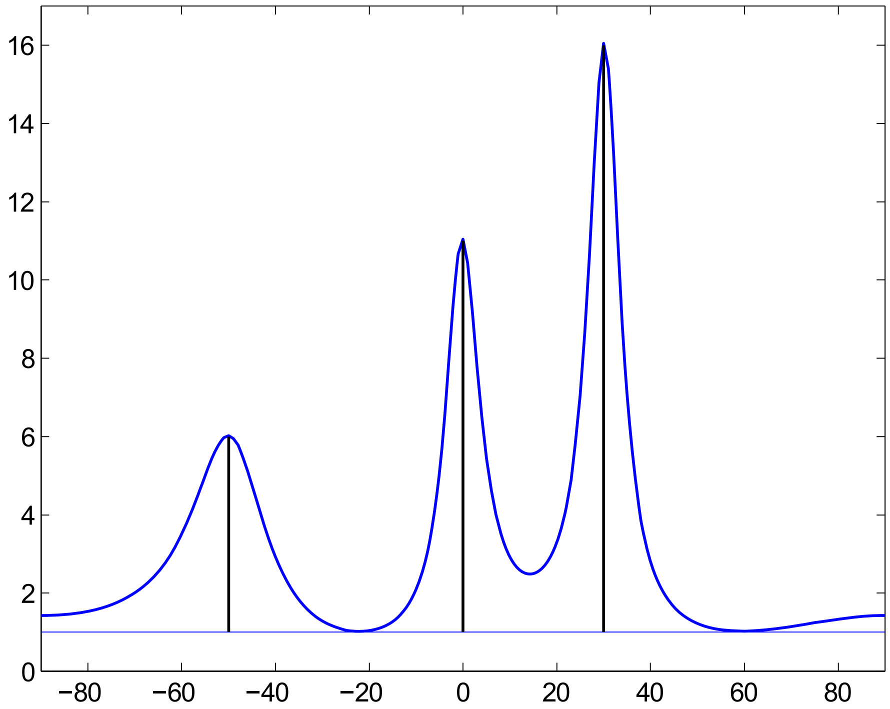
Capon Method

- Images to given 3 point sources

by Fourier Method



by Capon Method



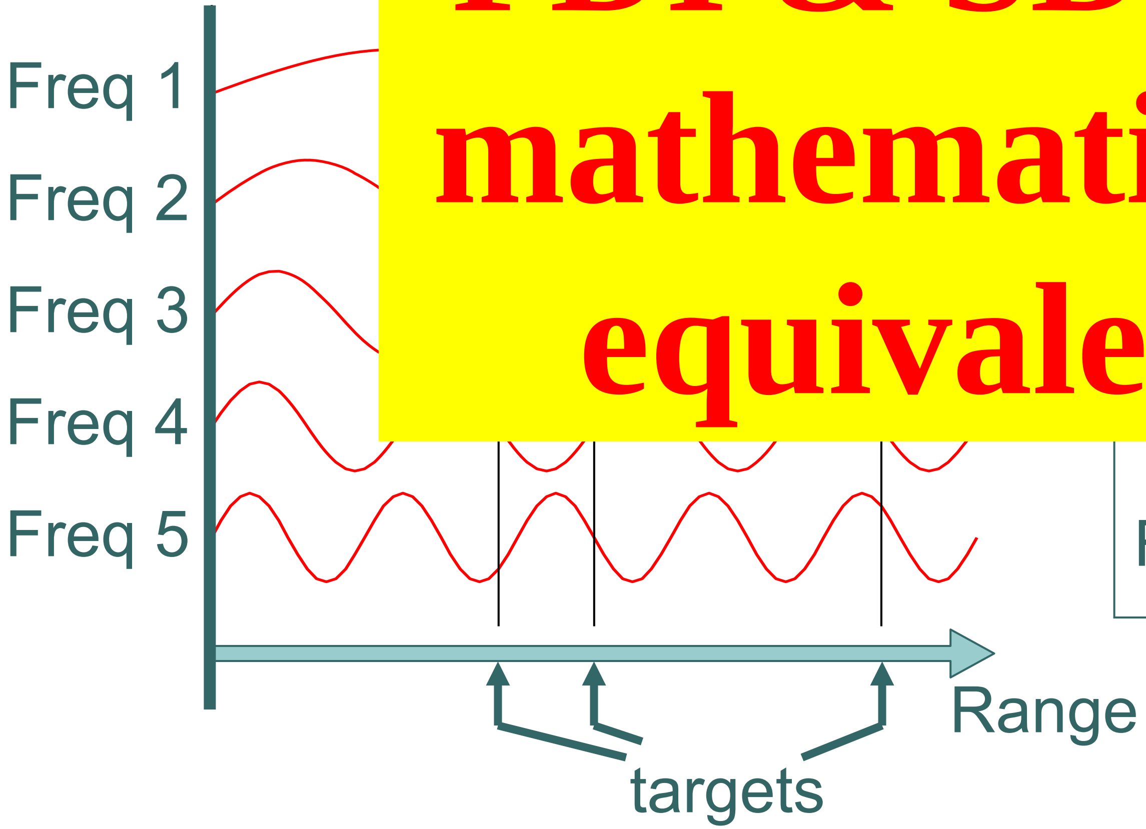
- Resolution depends on S/N

System in Frequency Domain: FDI

- Same principle can be applied to
frequ

rity

FDI & SDI are mathematically equivalent!



Angular Space

Angle

Freqs

Multiple Antenna

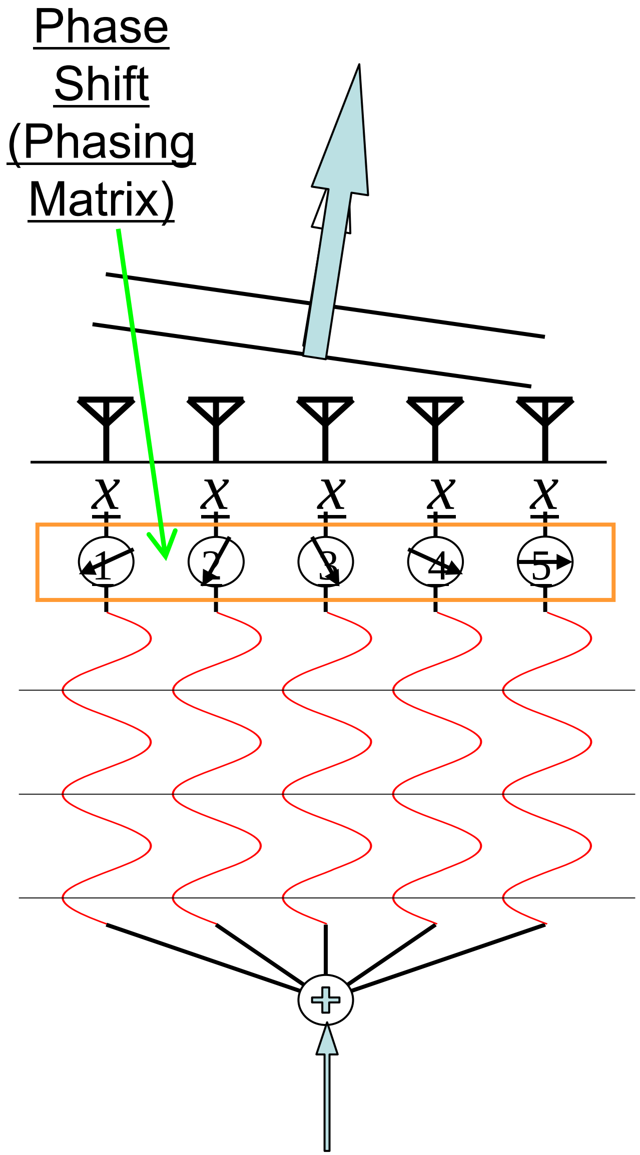
Frequency ⟺ Antenna Position

FDI range imaging

SDI angular imaging

SDI "initial phase" determination

- In case of SDI (adaptive beam forming using multiple antennas and multiple Rxs), Tx pulse is transmitted from all the antennas "simultaneously" (without any time differences (or with well-defined time delay in phasing matrix)), and all the "phase differences" among all the Tx paths inside the radar H/W (including phasing matrix) can be measured in advance and thus are well defined.
- This means that, in case of SDI, there is NO "initial phase" ambiguity among each Tx-Rx paths (inside radar H/W), and then angular power distribution can be determined (i.e., "beams" can accurately be formed) without any ambiguity (so SDI should work w/o problem!).
- Only phase distribution (angular space image) seen from the radar can be known. But real target distribution might not be known due to unknown and temporally varying radio wave propagation paths outside the radar H/W.

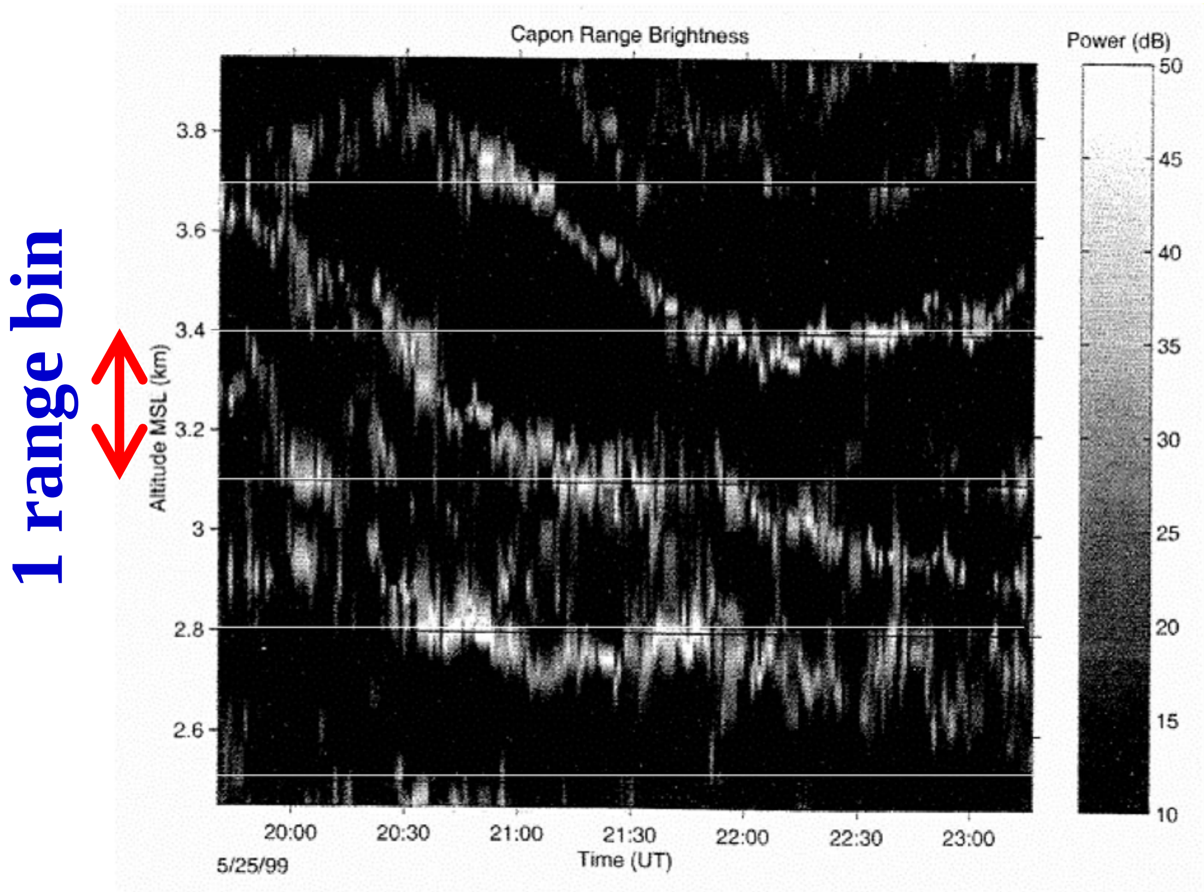


FDI "initial phase" determination

- in case of FDI, each FDI frequency are transmitted separately (at different timings, normally sequentially).
  So the initial phase offset for each Tx frequency (ultimately at DDS synthesizer) are random and cannot be determined / measured / controlled easily inside the radar H/W level.
- for FDI to work properly (i.e., for FDI to produce meaningful solution (or "beams" in SDI) for echo power distribution or range imaging), "initial (relative) phase" (at a certain time) among the FDI frequencies (i.e., for each FDI frequency against other FDI frequencies) must be determined (in case of # of freq >=3). This provides the real solution (range power distribution) except absolute range offset (<range bin (15km)).
- If initial phase cannot be determined, it is like a radar whose phasing matrix has random and unknown phase-shifts so it is difficult/impossible to form any proper beams...

FDI "initial phase" determination

- FDI method does NOT provide the absolute range offset (i.e., absolute range power distribution within a range bin). It can be determined from, e.g., characteristics of continuity of echo range distribution over ranges.



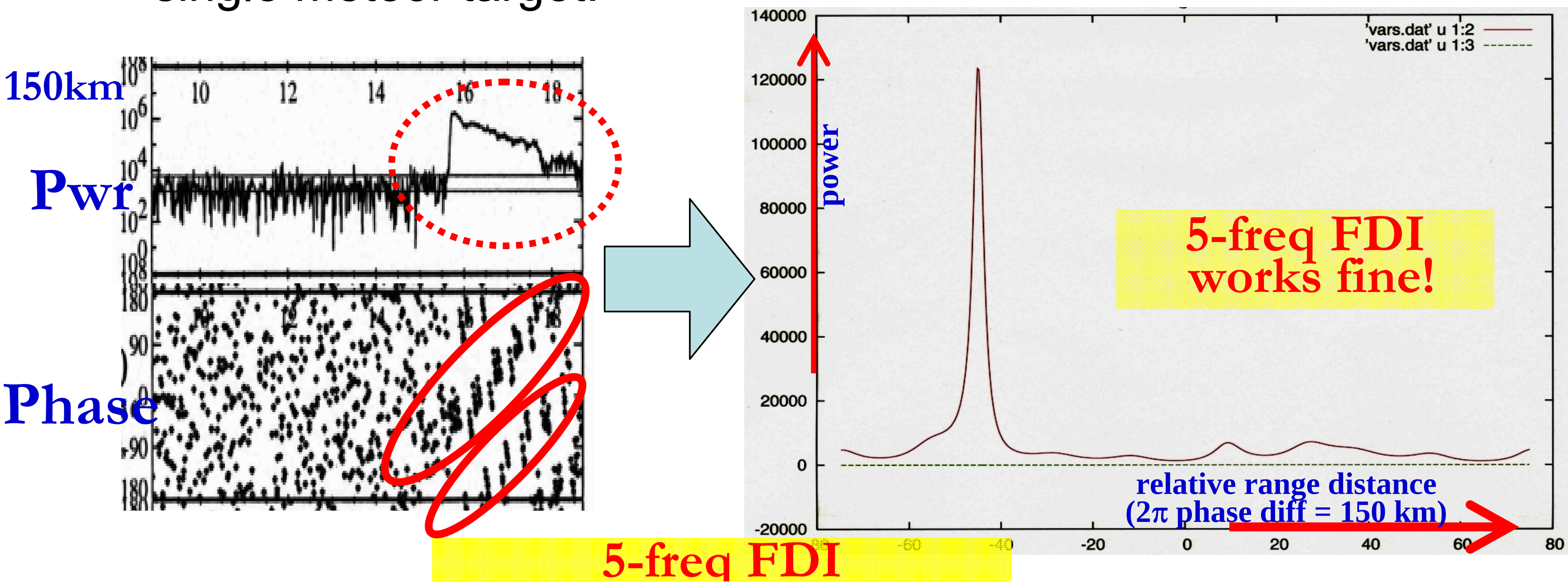
4-freq FDI
echo Power by ST radar.

original rsep=300m

FDI resolved much thinner turbalence layer structures within range cells

FDI "initial phase" determination

- To determine FDI "initial phase", near-range meteor echoes are thought to be able to be used as they are well-known and simple targets. Especially for cases of # of FDI freq >=3, relative initial phase can be determined so that the consequent power distribution in a range bin observing a meteor has just a sharp single peak corresponding the single meteor target.

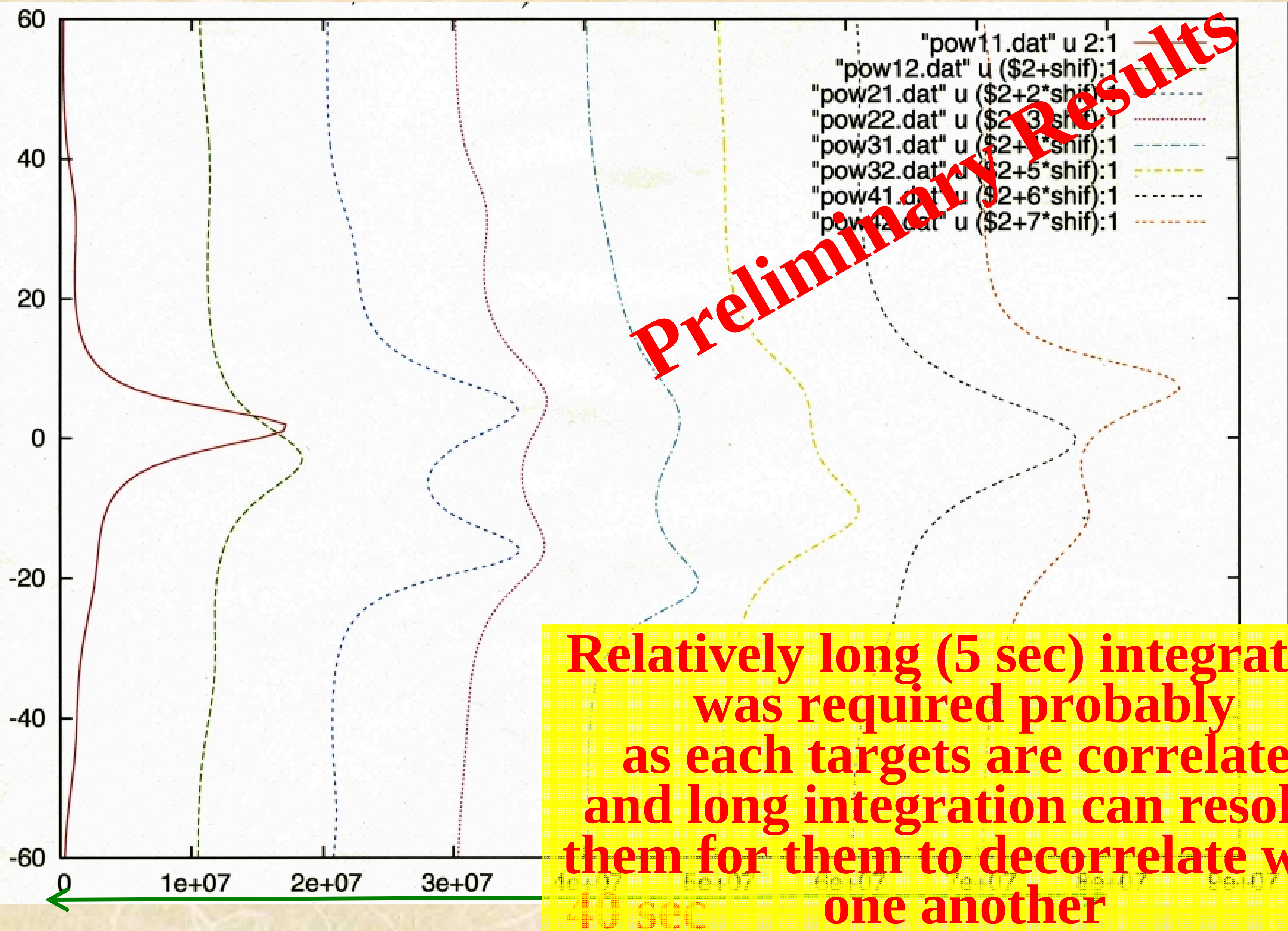


FDI "initial phase" determination

- Last year, authors tried to do this for 5-freq FDI and the FDI "initial phases" could be determined without any problem.
- HOWEVER, the initial phases obtained from a near-range meteor echo could NOT be used for further range FDI data analysis, probably because of different radio wave propagation paths for each FDI frequencies and/or those temporal variation.
- So as the "last resort", initial phases were determined from the far target (artificial FAIs) echoes themselves assuming that there is only one distribution peak in a range bin at a certain observation time. (This assumption was well-grounded from detail investigation of time variation of I/Q or power/phase data.) Another assumption of constant initial phases long enough over the observation period could provide the meaningful time variation of range image (Was it lucky?).
- But there are no reason that propagation paths are always constant and then initial phases does not change over time...

range#60

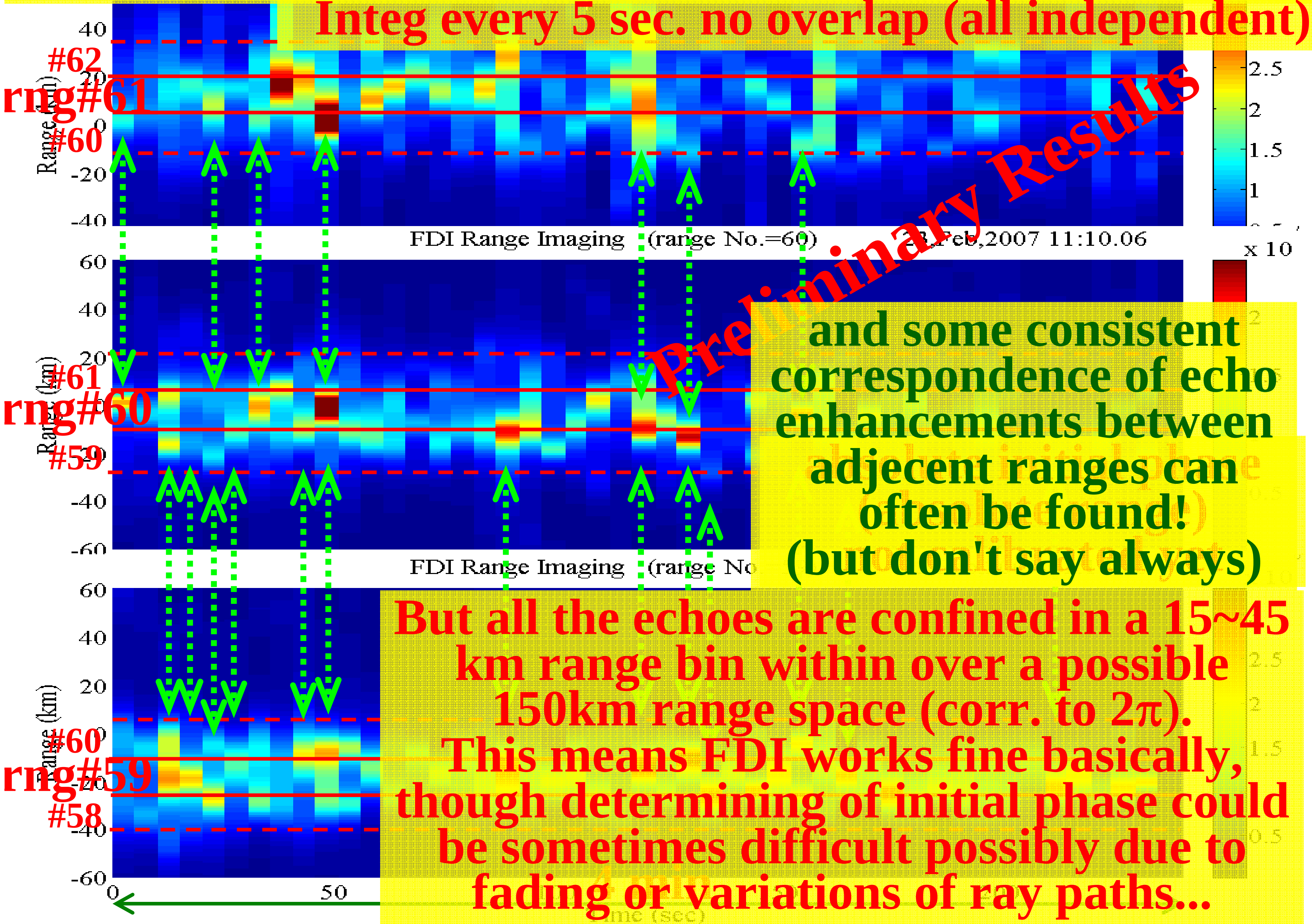
Integ every 5 sec. no overlap (all independent) with Capon estimator



Relatively long (5 sec) integration was required probably as each targets are correlated and long integration can resolve them for them to decorrelate with one another

SD Multi-Freq FDI Range Imaging Initial Results (Capon)

Integ every 5 sec. no overlap (all independent)



and some consistent correspondence of echo enhancements between adjecent ranges can often be found! (but don't say always)

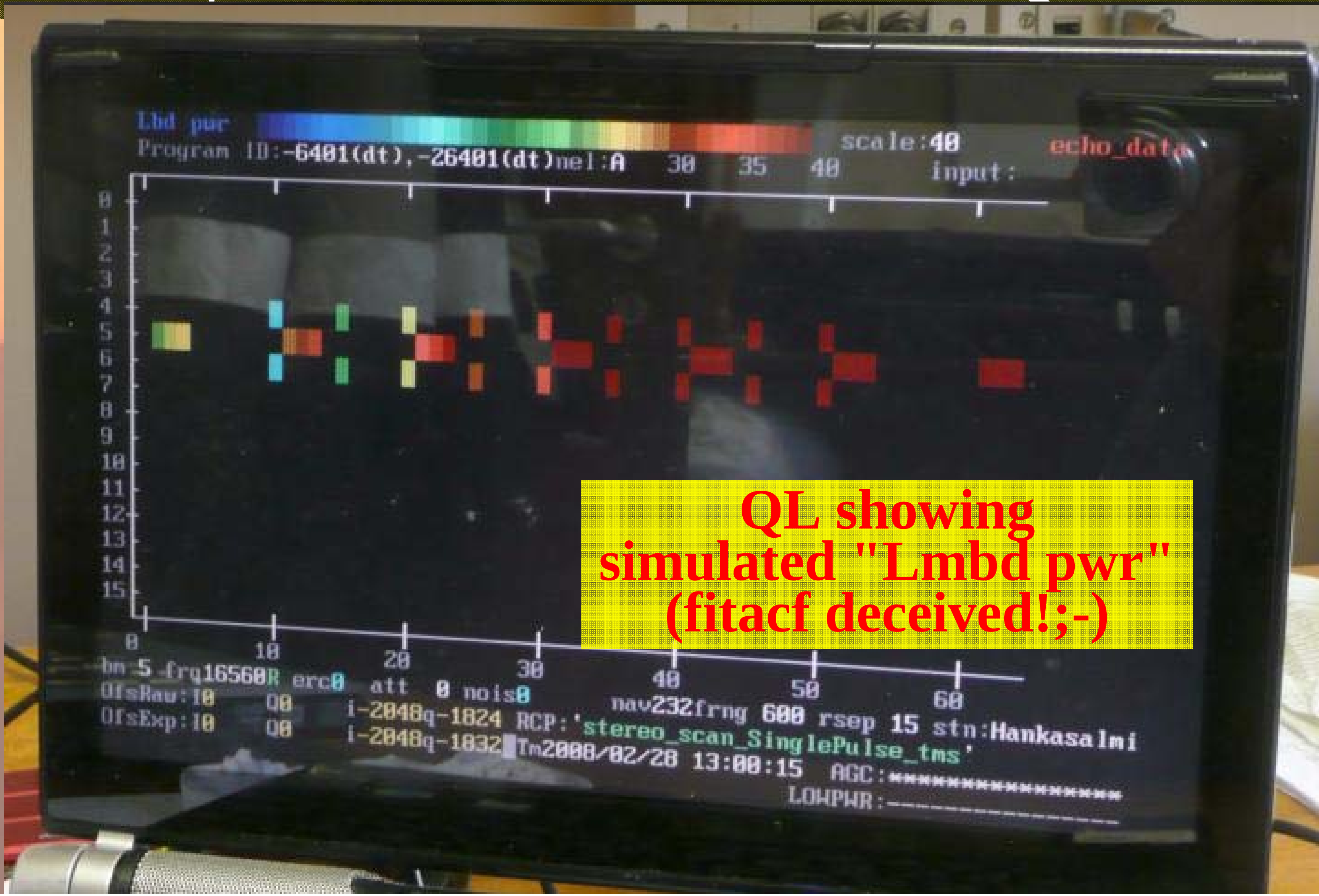
But all the echoes are confined in a 15~45 km range bin within over a possible 150km range space (corr. to 2π). This means FDI works fine basically, though determining of initial phase could be sometimes difficult possibly due to fading or variations of ray paths...

more improved version of FDI?

- To obtain the results done last year, 5-sec period of data are required to get one stable fine resolution image.
- This was partly because frequency was unchanged during each pulse sequence of ~100msec to obtain conventional ACFs without problem, and thus one cycle of FDI frequency scan took about 0.5 sec for 5-freq FDI. Also longer "integration" was thought to be required partly and possibly also because the FAIs' echo powers were highly temporally varying and also had long correlation time.
- To improve the temporal resolution, it's the best to reduce the time to complete each FDI frequency scan.
- Therefore, we made our mind to move from multi-pulse observation to single (or double) pulse scheme to reduce the time for each FDI cycle. To make sure not to be contaminated by cross range noise, IPP was set to ~20msec (3000km).
- We cannot use fitacf for this mode but we can do any preferable spectral analysis using TMS IQ data.

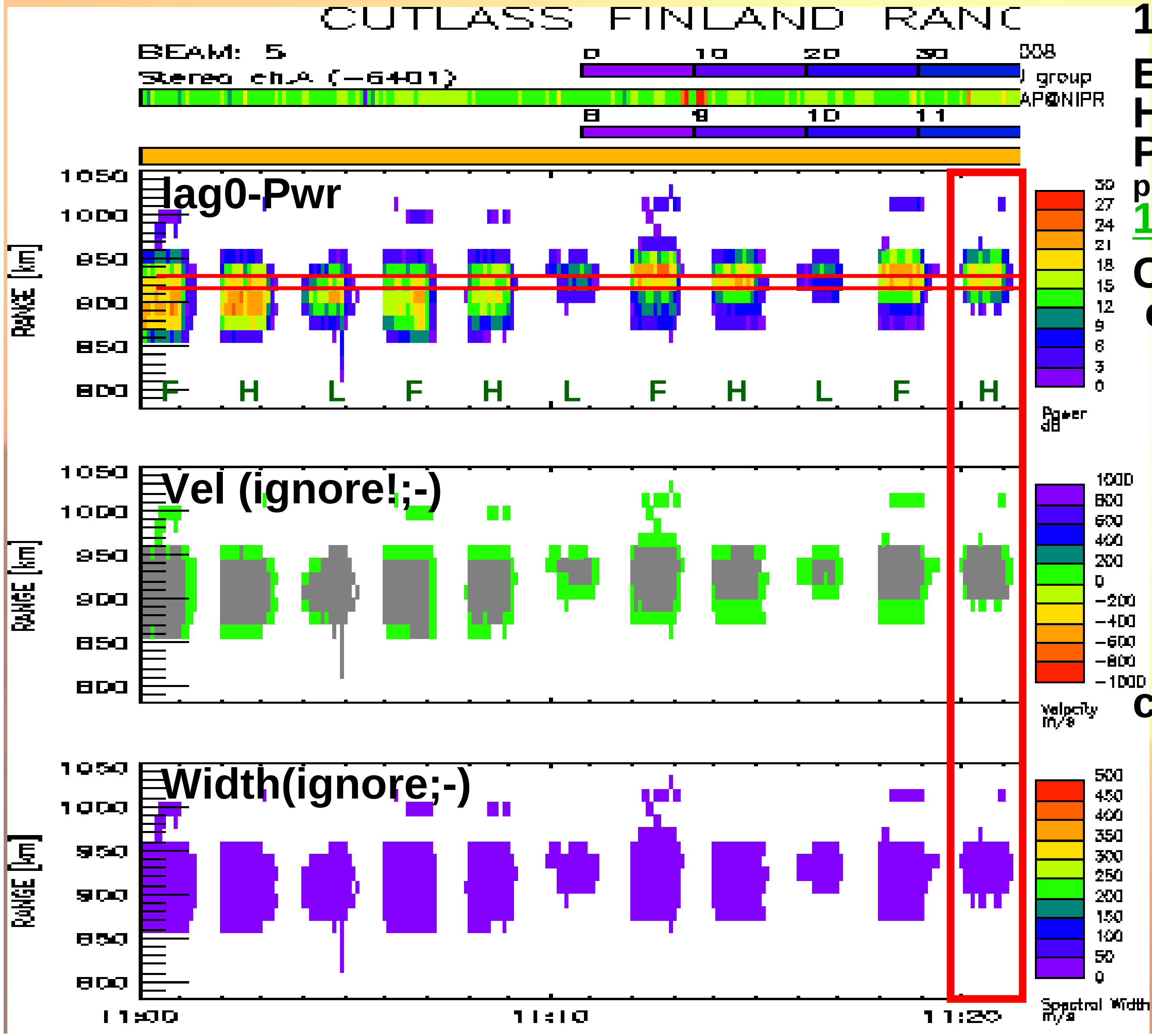
deceive fitacf...;-)

★ Fitacf was a bit modified to show us lag0pwr as lambda power so that echo power can be seen for real-time checking...



QL showing simulated "Lmbd pwr" (fitacf deceived!;-)

Heating experiment this time



2008/03/07
11:19:00-11:20:00UT

EISCAT Tromso
Heater 4.04MHz
Power: 85kW-3dB
power stepping 0/-3/-10dB
1min ON/1min Off

CUTLASS Finland
chA
- **double pulse TMS**
- **mpinc=2400μsec**
- **rsep=15km, intt=6s**
- **nsmp=224(3000km)**
- **5-frq FDI**
- **Frq=16570~94kHz**
- **ΔF=3,3,9,9kHz**
- **minΔF=3kHz**
- **maxΔF=24kHz**

chB
- **single pulse TMS**
- **rsep=15km , intt=6s**
- **nsmp=200(3000km)**
- **5-frq FDI**
- **Frq=16555~67kHz**
- **ΔF=3,3,3,3kHz**
- **minΔF=3kHz**
- **maxΔF=12kHz**

High Res. Temporal Pwr variation for freqs

~10Hz

all 5 frqs

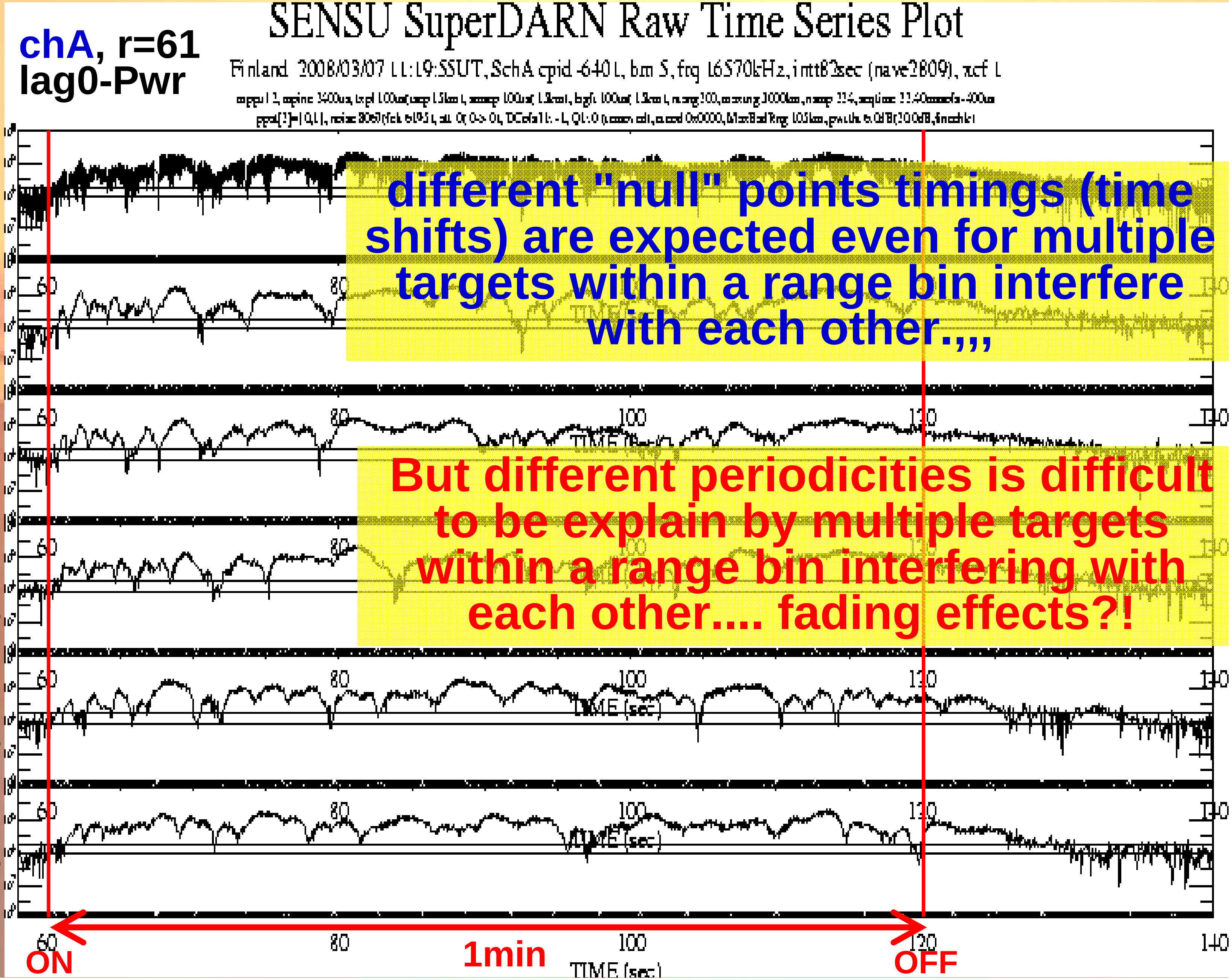
frq1 =16570kHz

frq2 =frq1+3 kHz

frq3 =frq2+3 kHz

frq4 =frq3+9 kHz

frq5 =frq4+9 kHz =16594kHz



High Res. Temporal Pwr variation for freqs

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=16555kHz

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frq3
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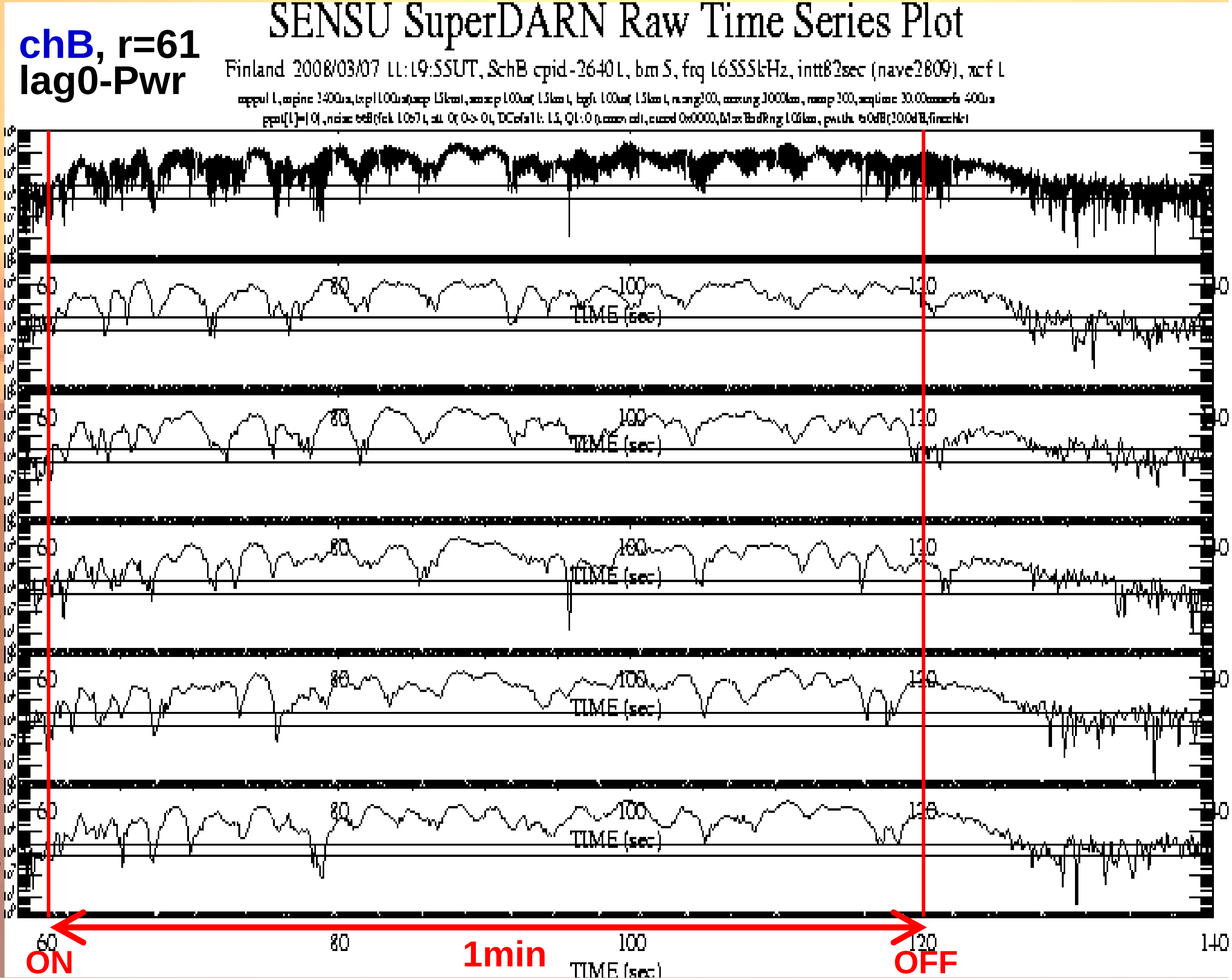
frq4
=frq3+3 kHz

frq5
=frq4+3 kHz
=16567kHz



Long duration Doppler Power Spectrum using any length of long period (say, every 10 sec) of data to obtain much finer freq resol., why not?

To obtain Power Spectrum with TMS Unequally spaced time series, just do the simple & primitive way..

$$Z(t_k)=I(t_k)+iQ(t_k)$$

$$S(\omega)=\sum_{\text{all } k} Z(t_k)*\exp(-i\omega t_k)$$

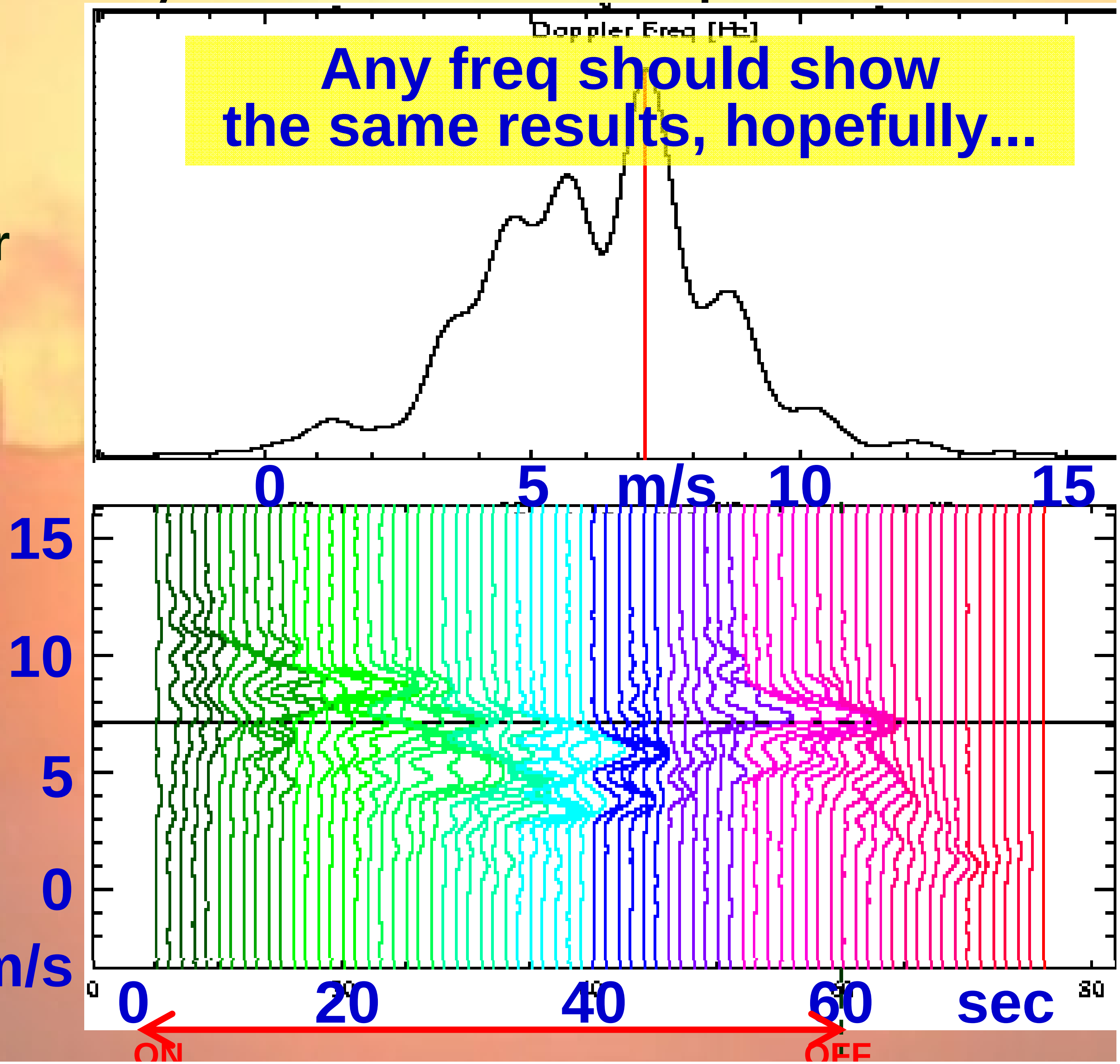
$$PS(\omega)=|S(\omega)|^2$$

High Res. Dynamic Power Spectrum

chA
Freq#1

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)

High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum

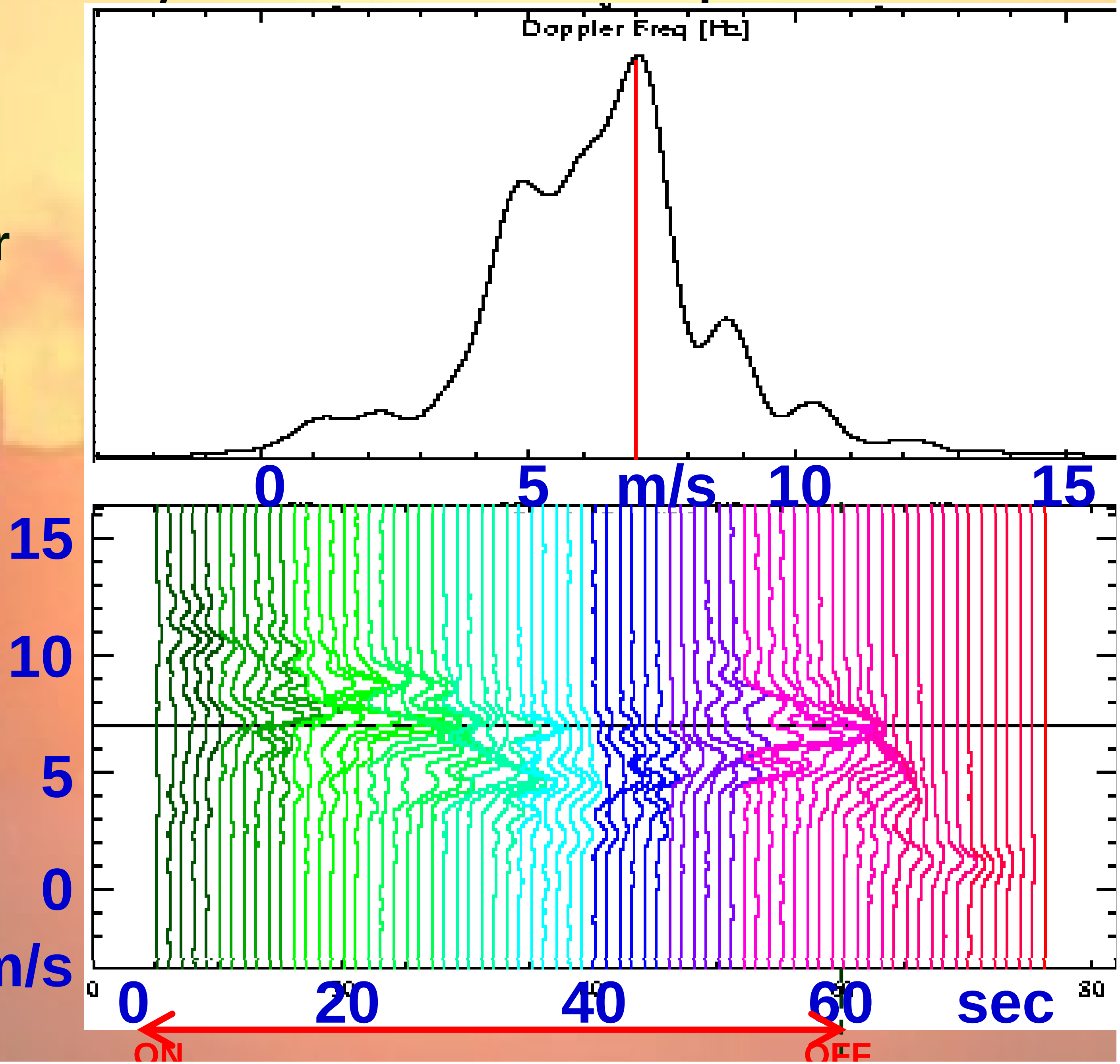


High Res. Dynamic Power Spectrum

chA
Freq#2

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)

High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum

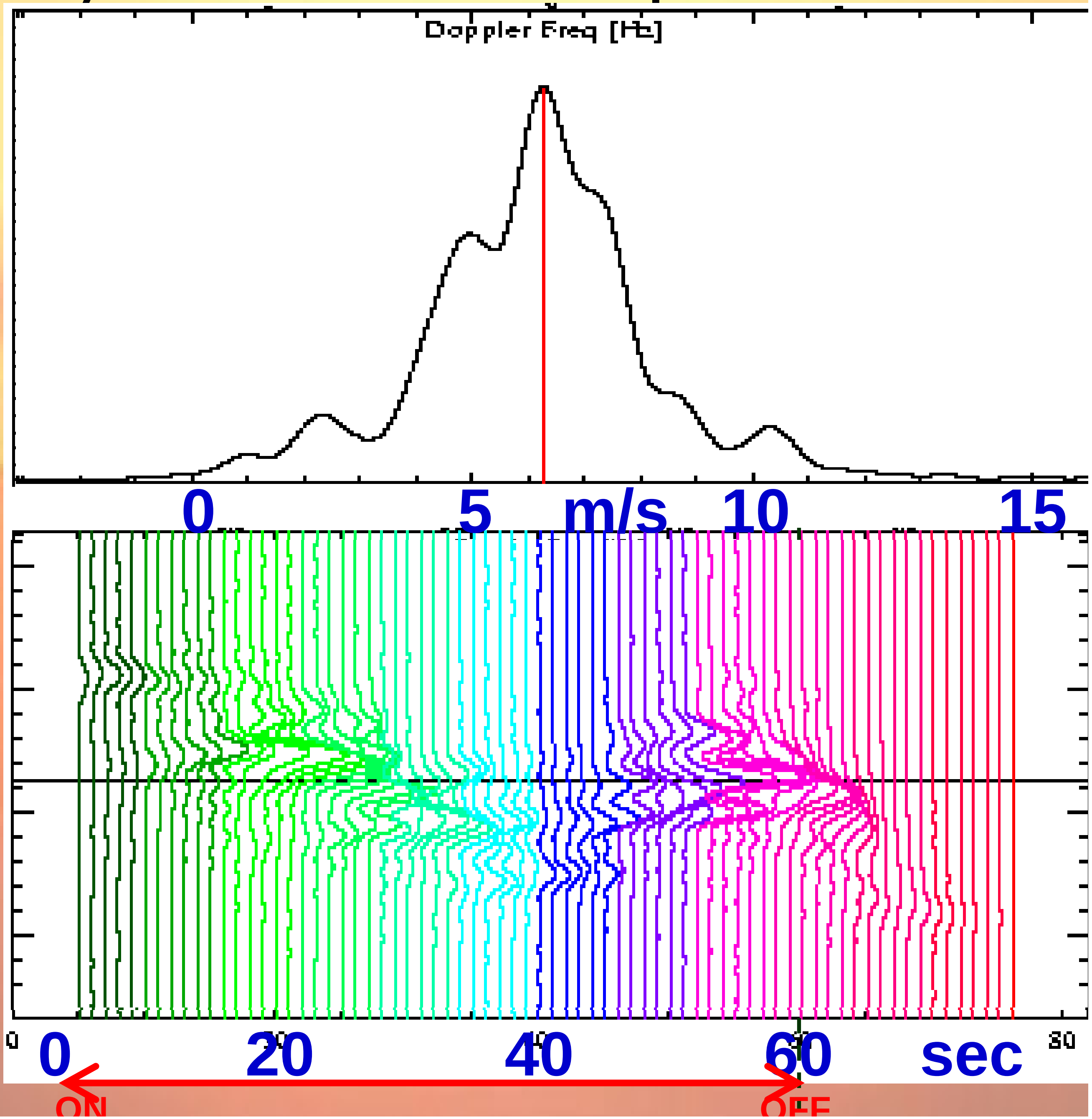


High Res. Dynamic Power Spectrum

chA
Freq#3

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)

High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum

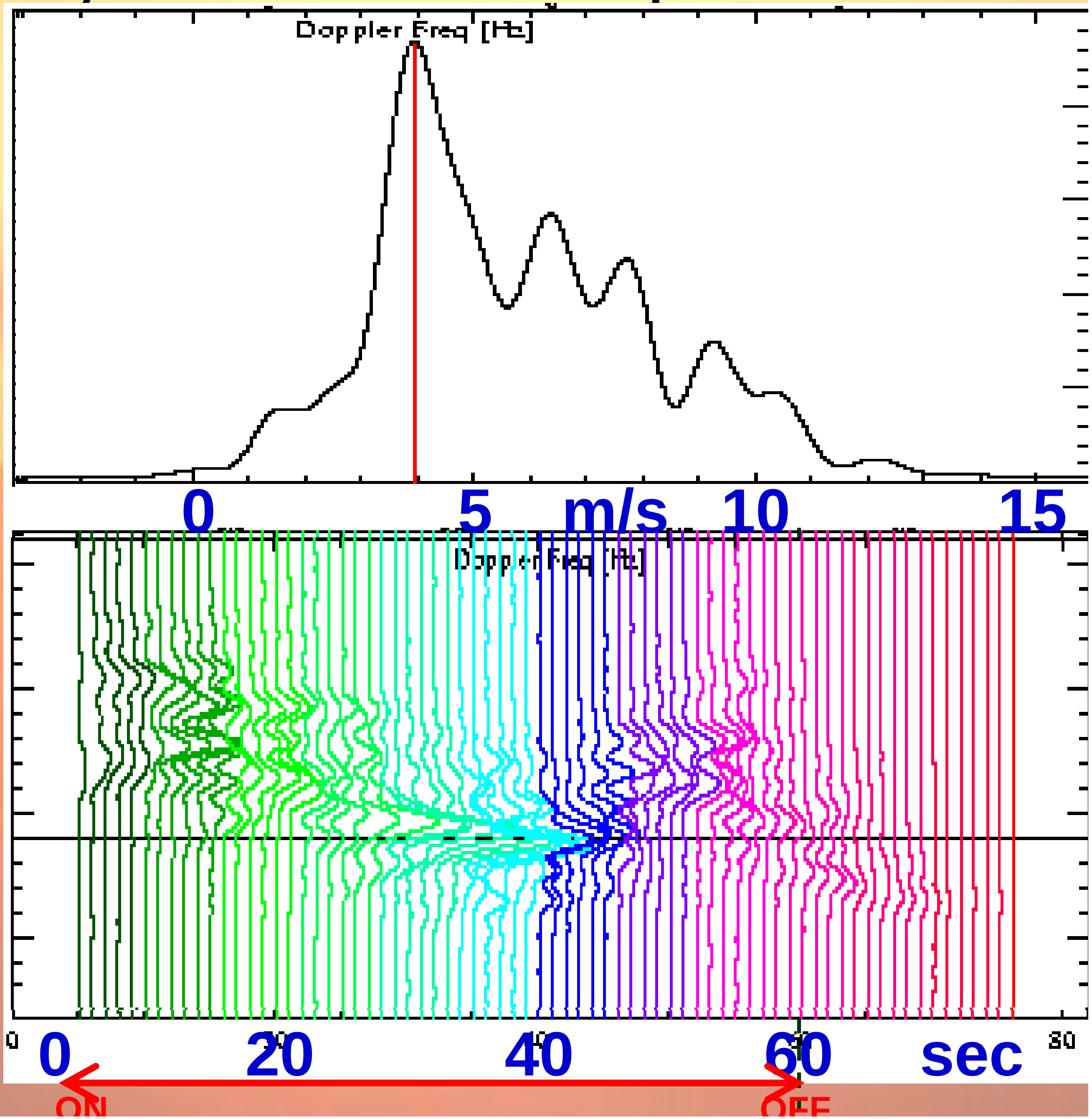


High Res. Dynamic Power Spectrum

chA
Freq#4

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)

High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum

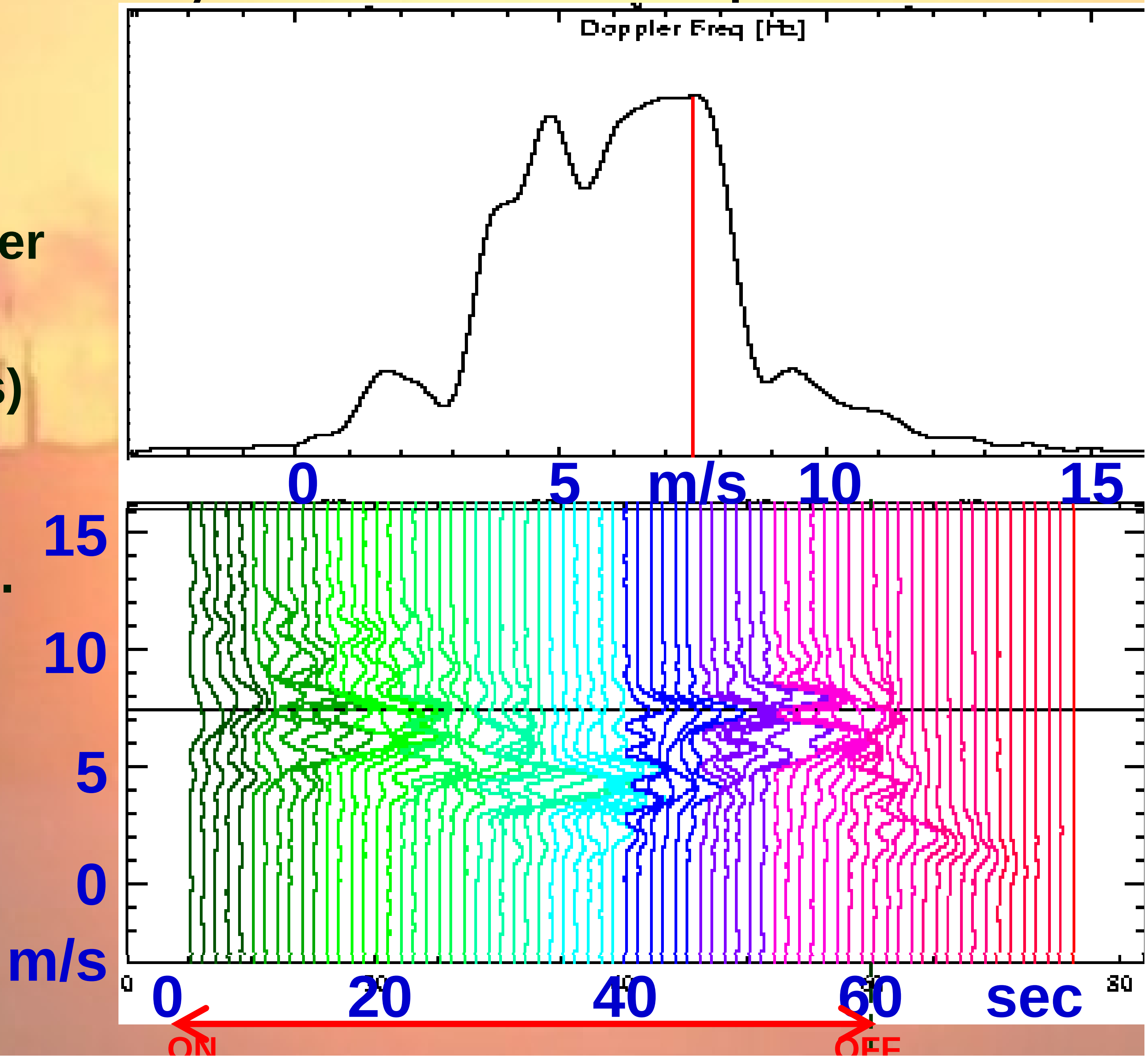


High Res. Dynamic Power Spectrum

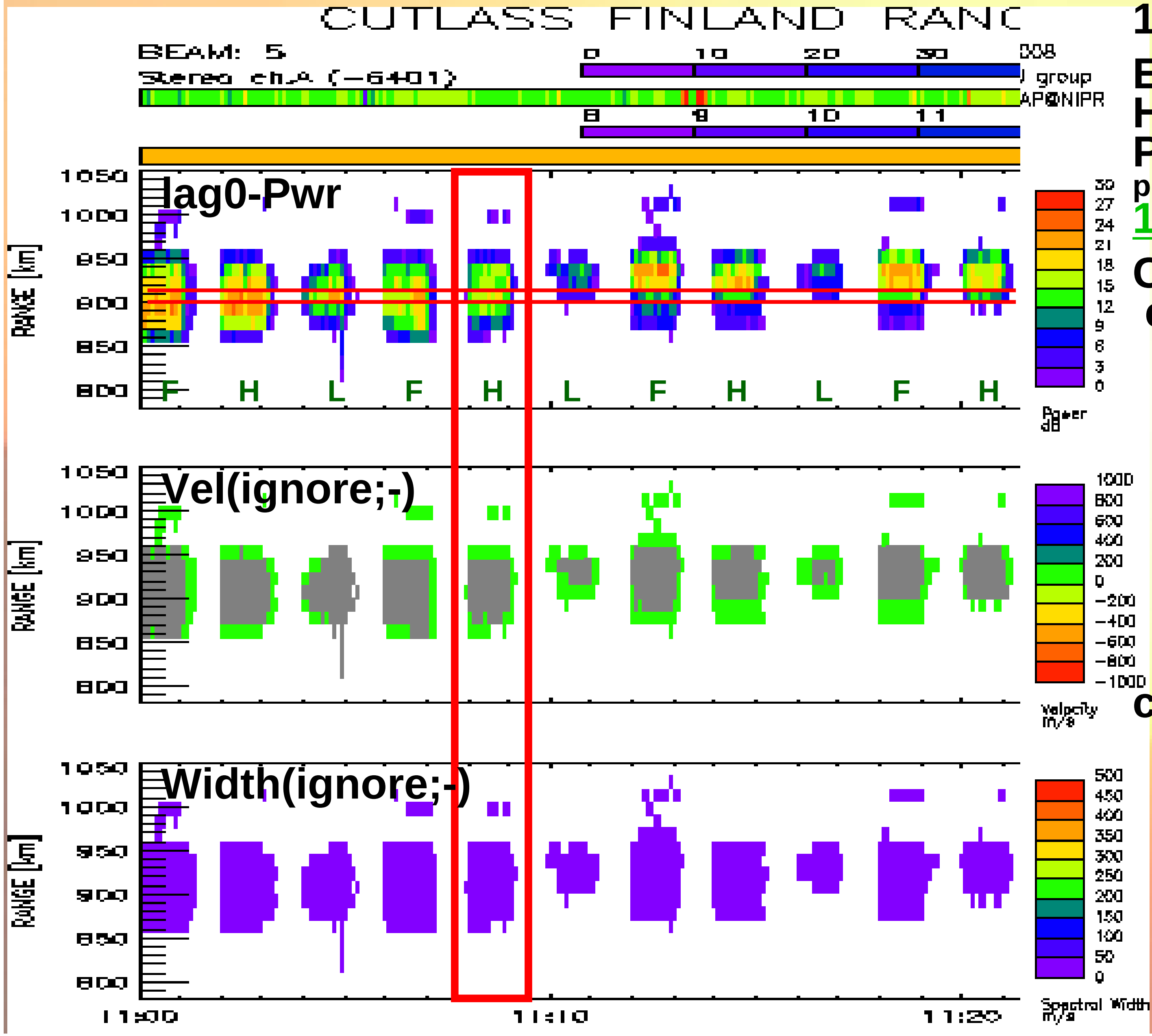
chA
Freq#5

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)

High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum



Heating experiment this time



2008/03/07
11:08:00-11:09:00UT

EISCAT Tromso
Heater 4.04MHz
Power: 85kW-3dB
power stepping 0/-3/-10dB
1min ON/1min Off

CUTLASS Finland
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double pulse TMS
mpinc=2400μsec
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5-frq FDI
Frq=16560~84kHz
ΔF=3,3,9,9kHz
minΔF=3kHz
maxΔF=24kHz
chB
single pulse TMS
rsep=15km , intt=6s
nsmp=200(3000km)
5-frq FDI
Frq=16595~607kHz
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minΔF=3kHz
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High Res. Temporal Pwr variation for freqs

~10Hz

all 5 frqs

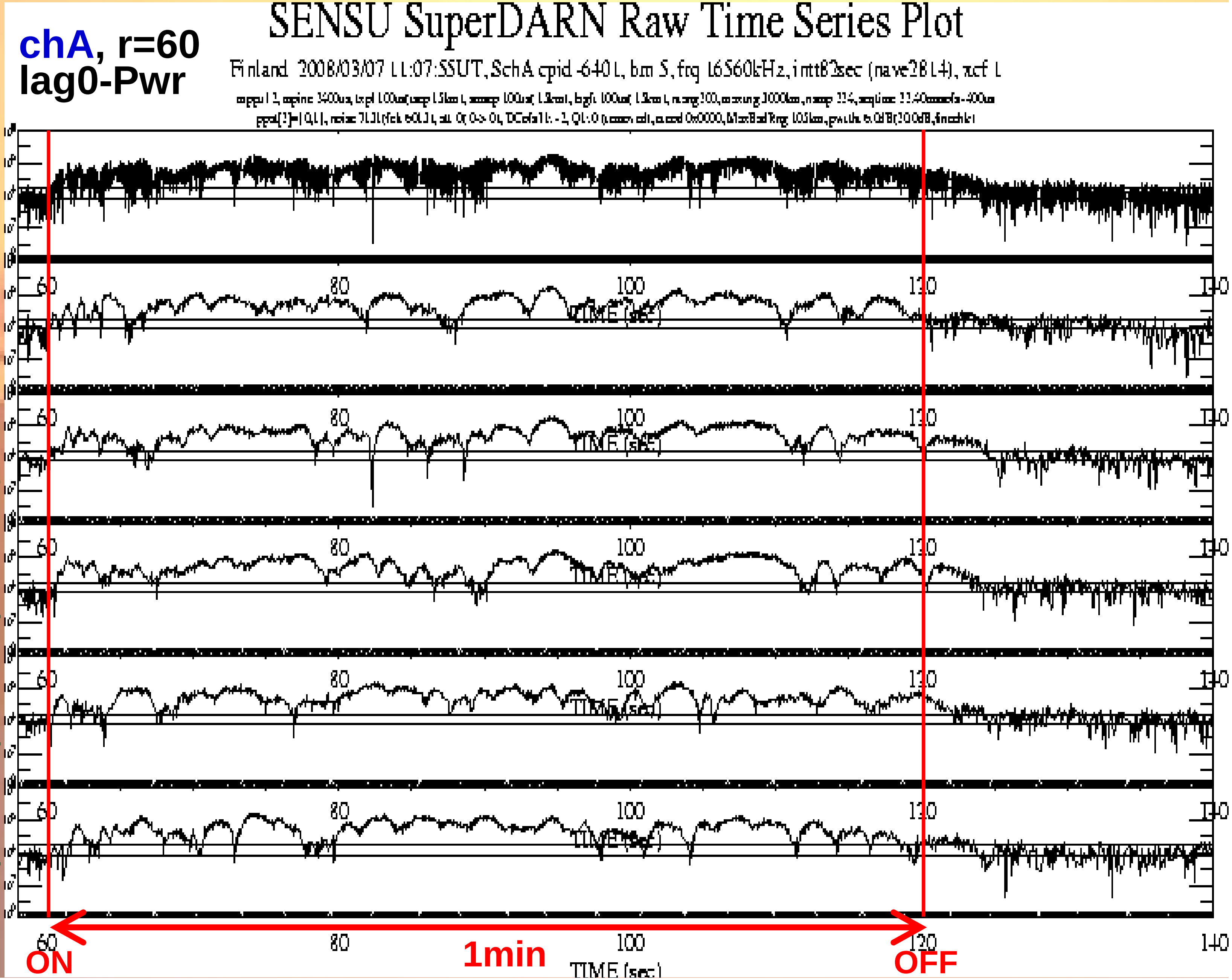
frq1 =16560kHz

frq2 =frq1+3 kHz

frq3 =frq2+3 kHz

frq4 =frq3+9 kHz

frq5 =frq4+9 kHz =16584kHz



High Res. Temporal Pwr variation for freqs

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all 5 frqs

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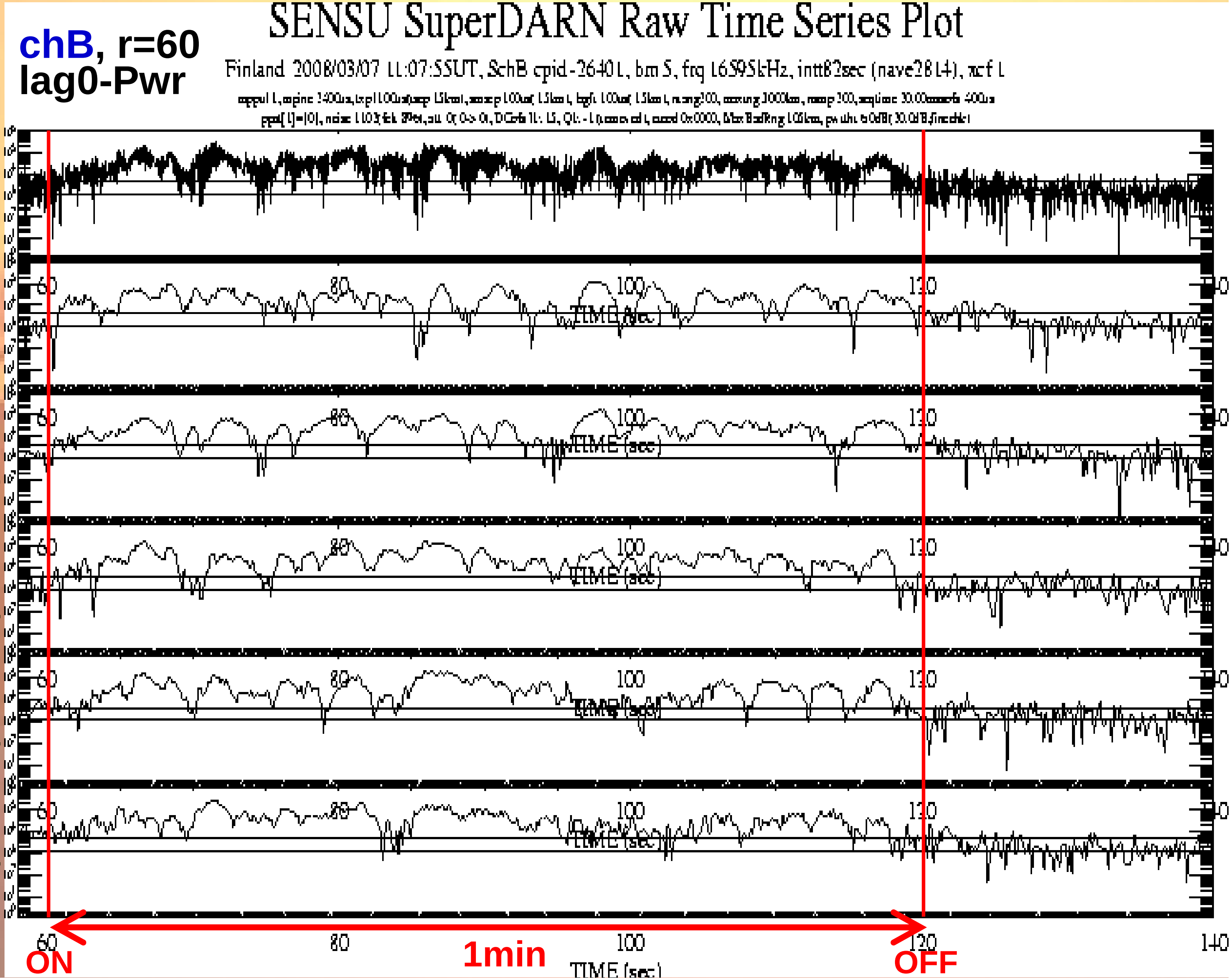
frq3
=frq2+3 kHz

frq4
=frq3+3 kHz

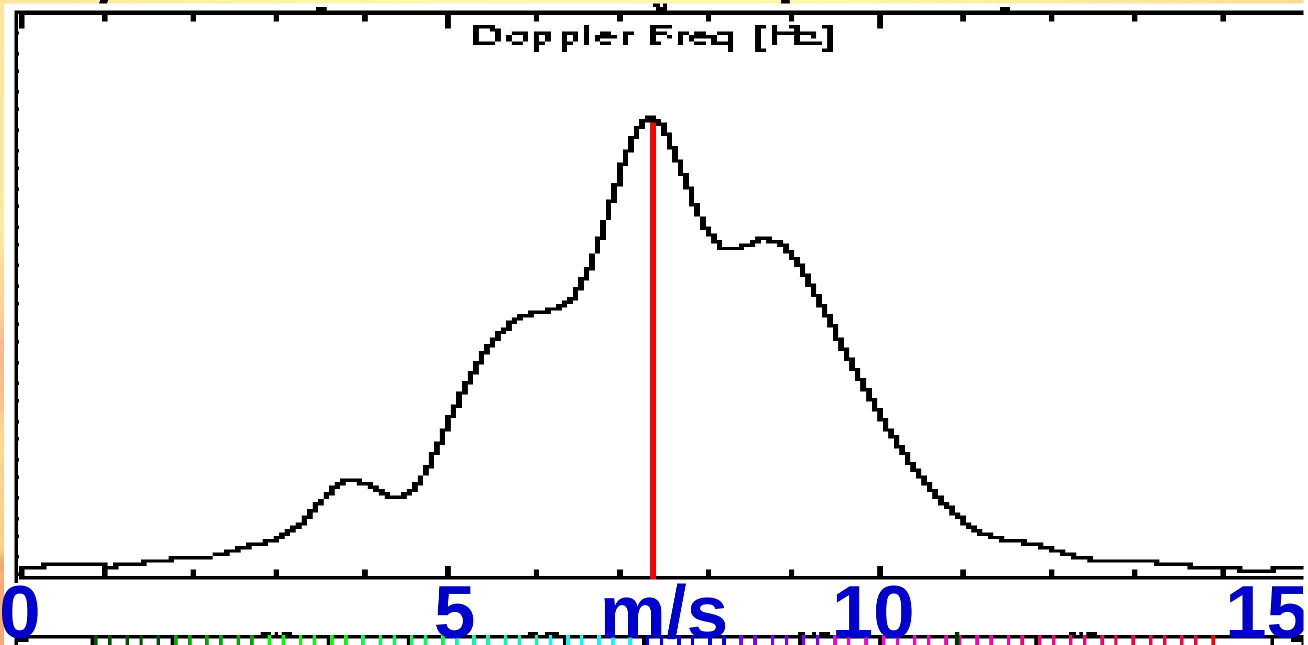
frq5
=frq4+3 kHz
=16607kHz



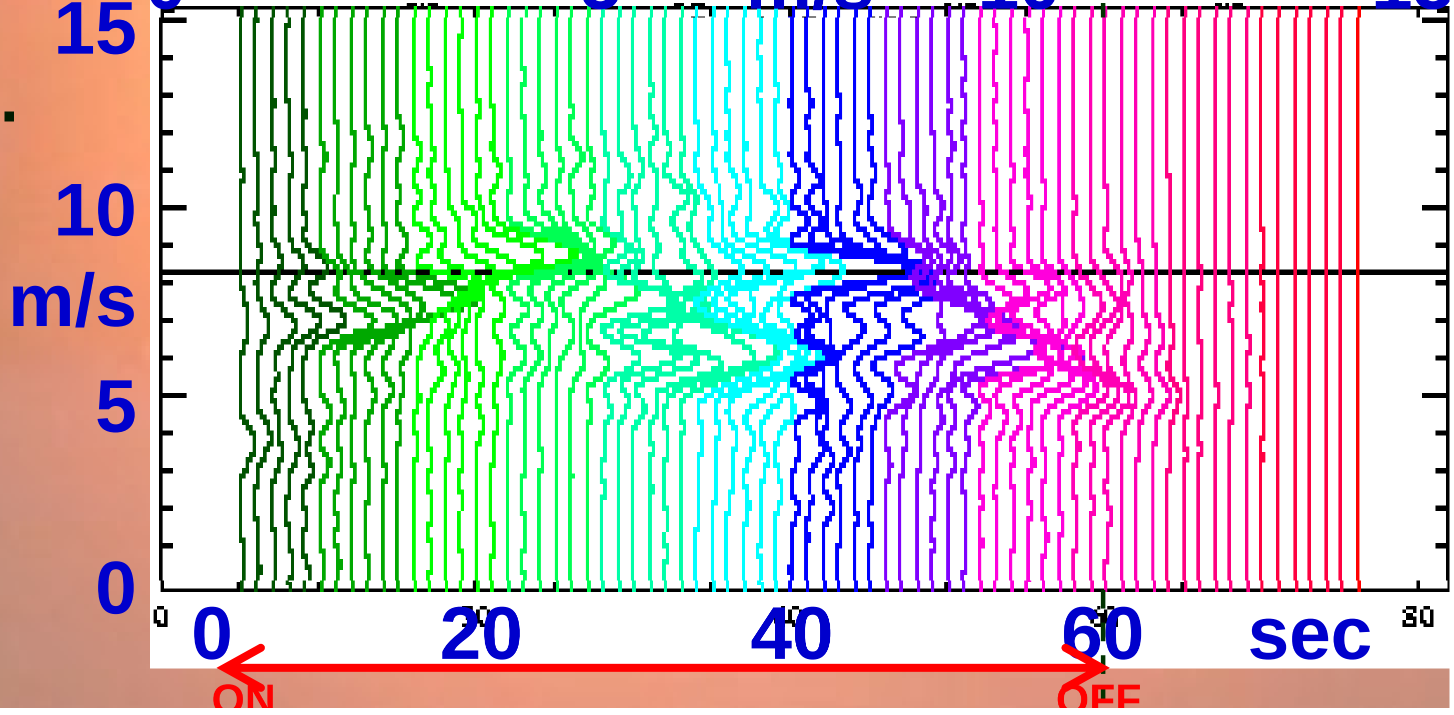
High Res. Dynamic Power Spectrum

chA
Freq#1

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)



High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum

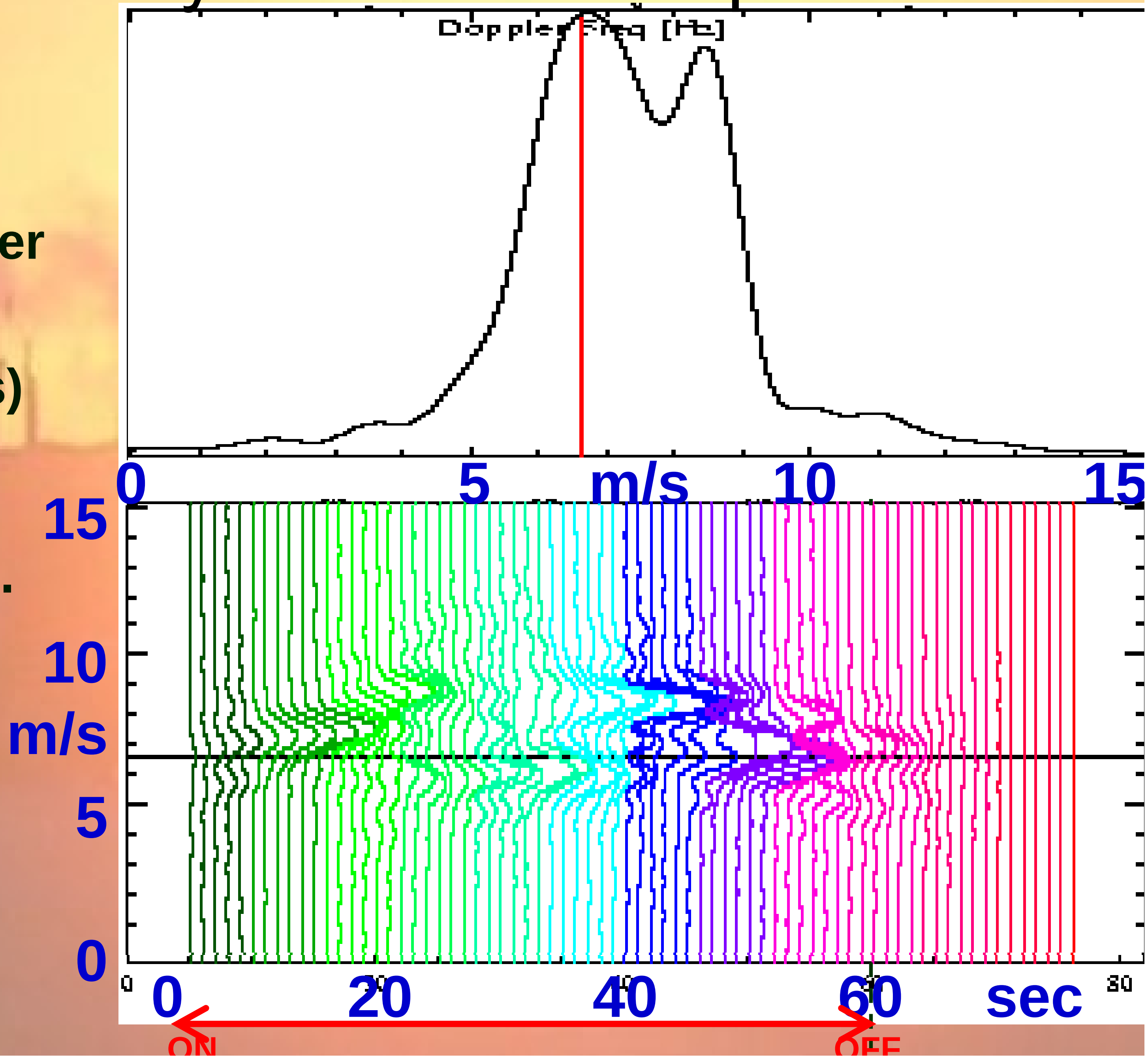


High Res. Dynamic Power Spectrum

chA
Freq#2

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)

High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum

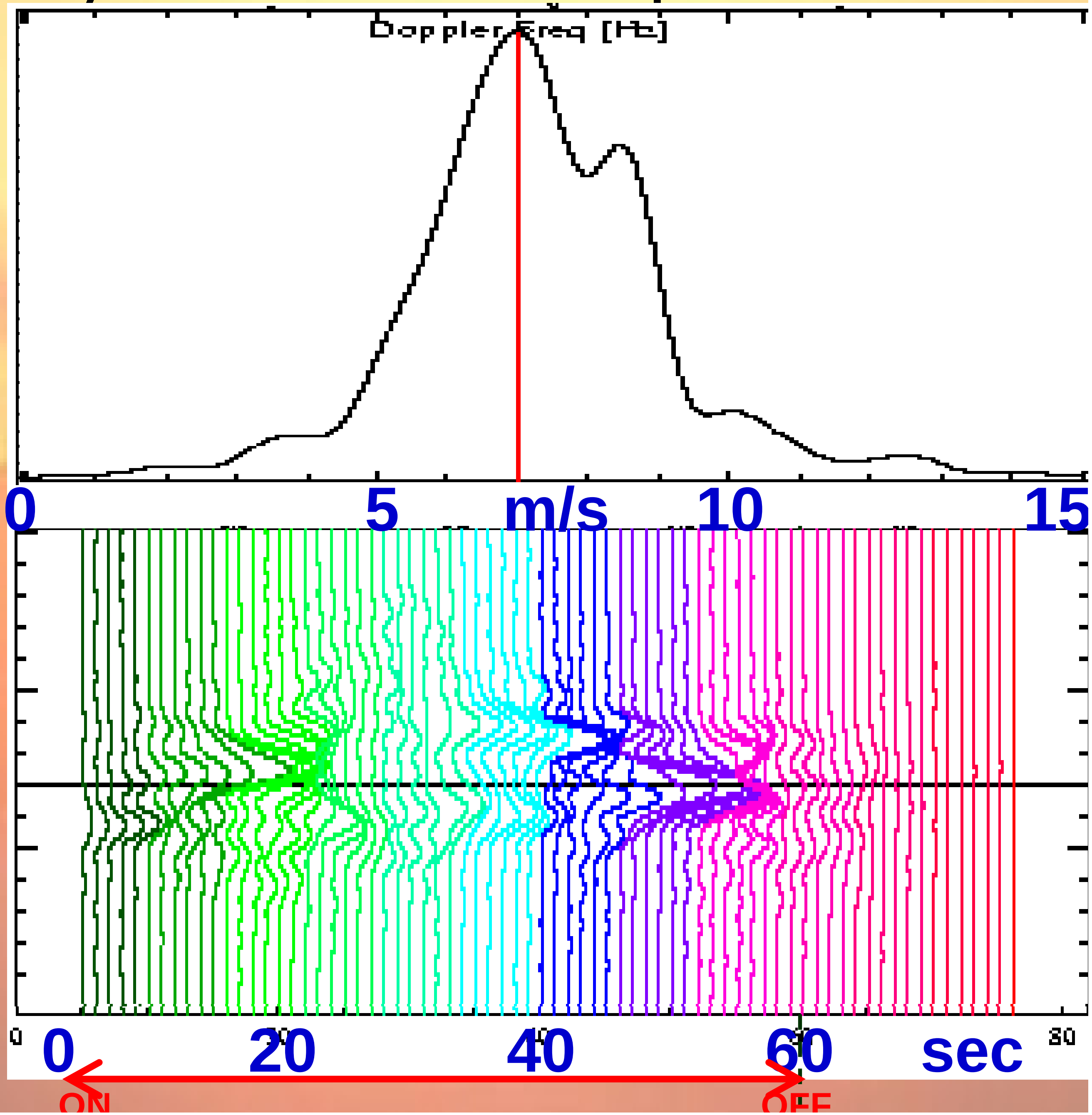


High Res. Dynamic Power Spectrum

chA
Freq#3

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)

High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum

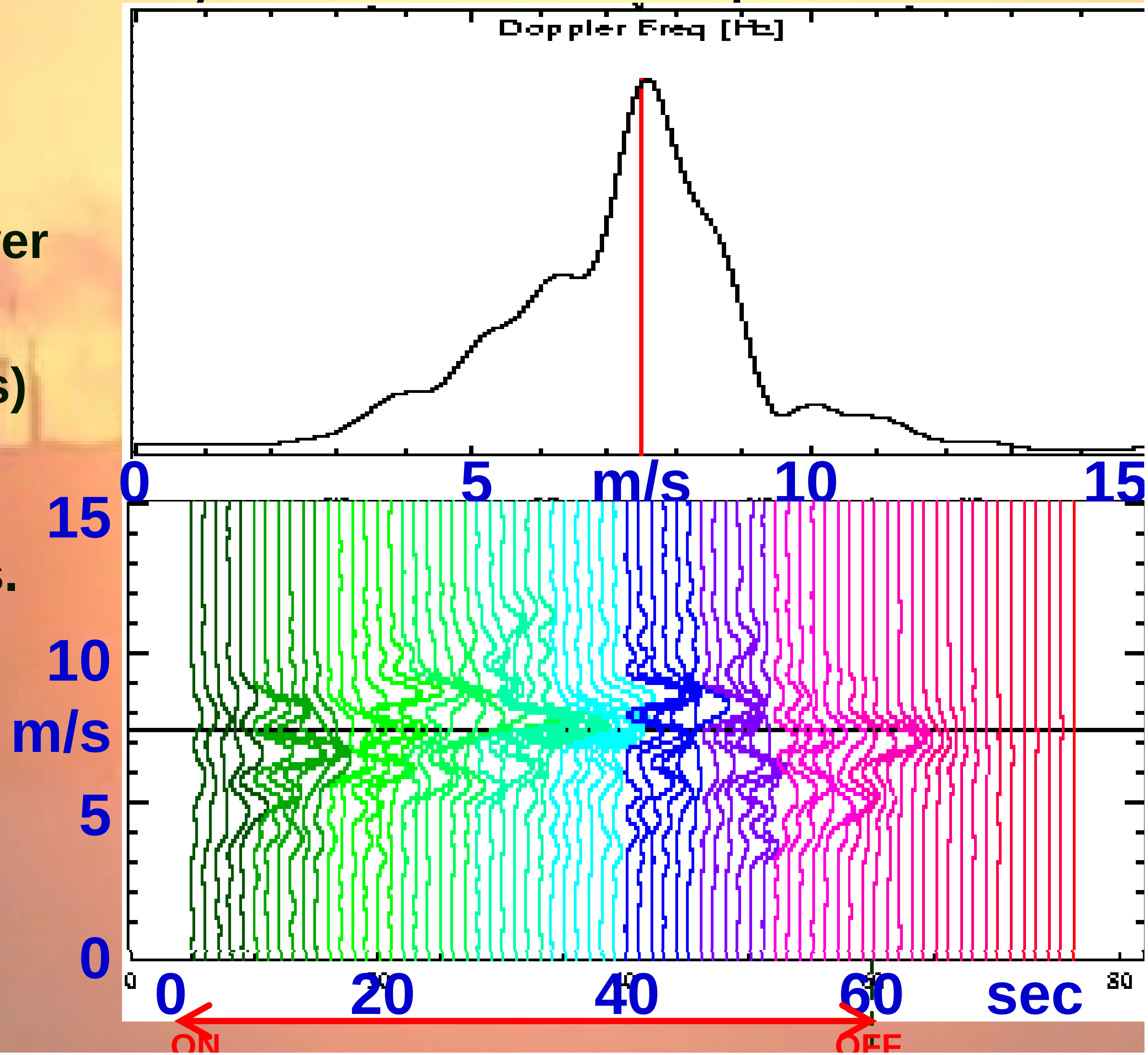


High Res. Dynamic Power Spectrum

chA
Freq#4

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)

High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum

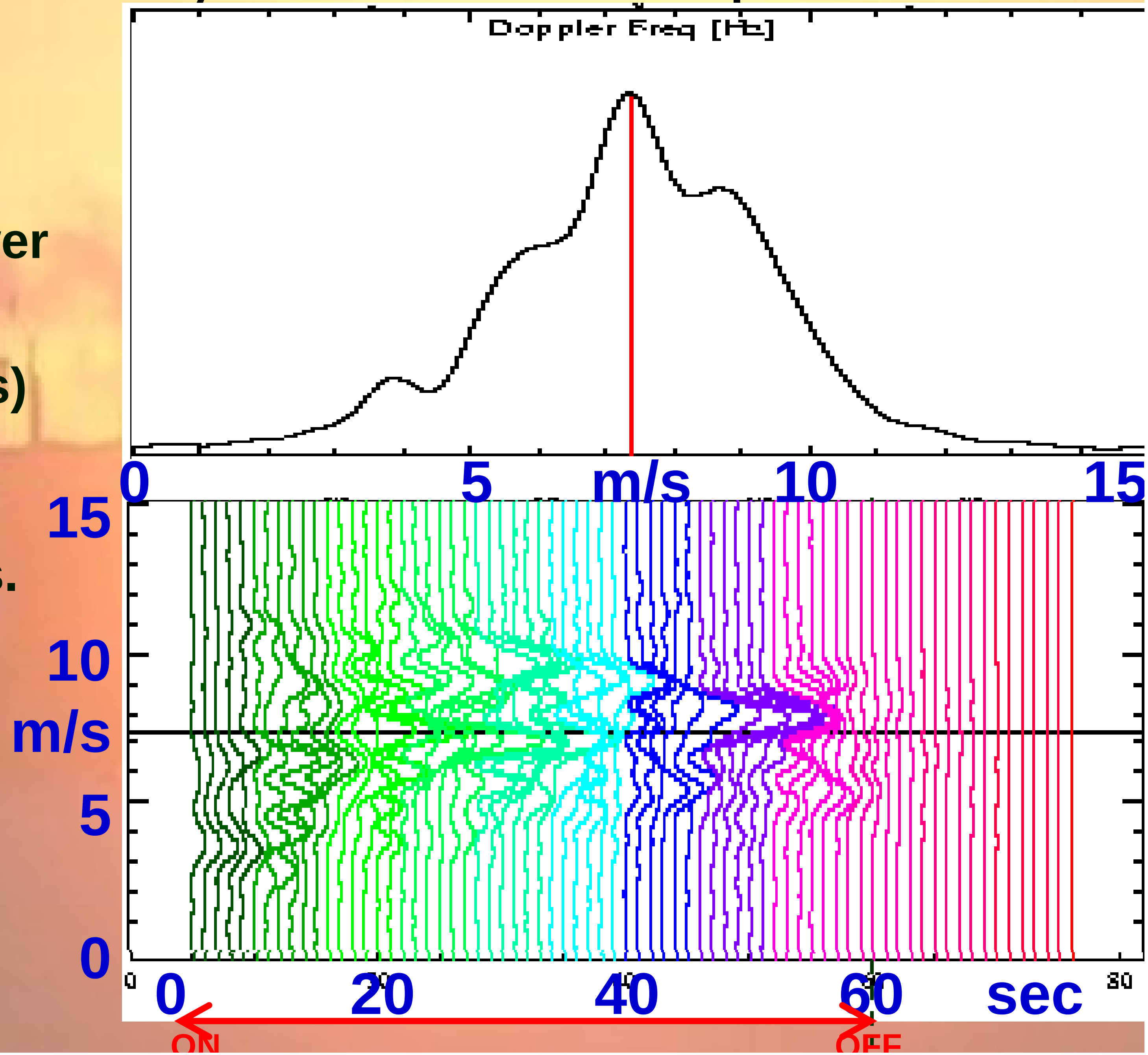


High Res. Dynamic Power Spectrum

chA
Freq#5

Average Doppler Power Spectrum for 80sec (res:~0.1m/s)

High freq res. (~1m/s) & high time Resol. Doppler Dynamic Power Spectrum



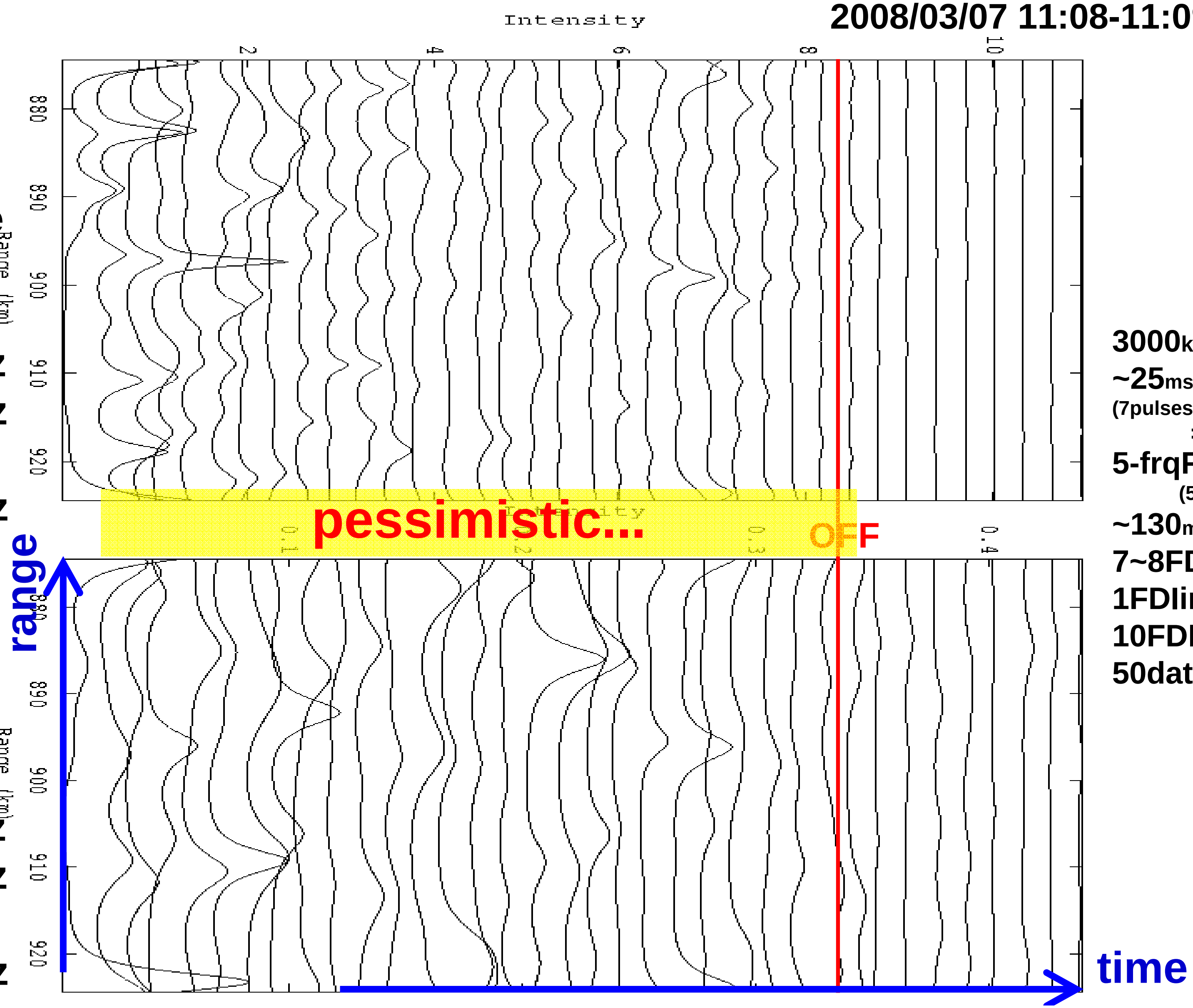
FDI results (for a worse case)

min.entropy applied only at t=0, & rest uses the same initial phases

2008/03/07 11:08-11:09

chA

double pulse
r=60(900km)
5-frq FDI
F1=16560kHz
Δf=3,3,9,9kHz
minΔf= 3kHz
maxΔf=24kHz



chB

single pulse
r=50(900km)
5-frq FDI
F1=16595kHz
Δf=3,3,3,3kHz
minΔf= 3kHz
maxΔf=12kHz

3000km=20ms
~25ms/seq
(7pulses:~90ms:
:~4 times)
5-frqFDI
(5data/FDI)
~130ms/FDI
7~8FDI/sec
1FDIimage=
10FDIseq=
50data/~1.3s

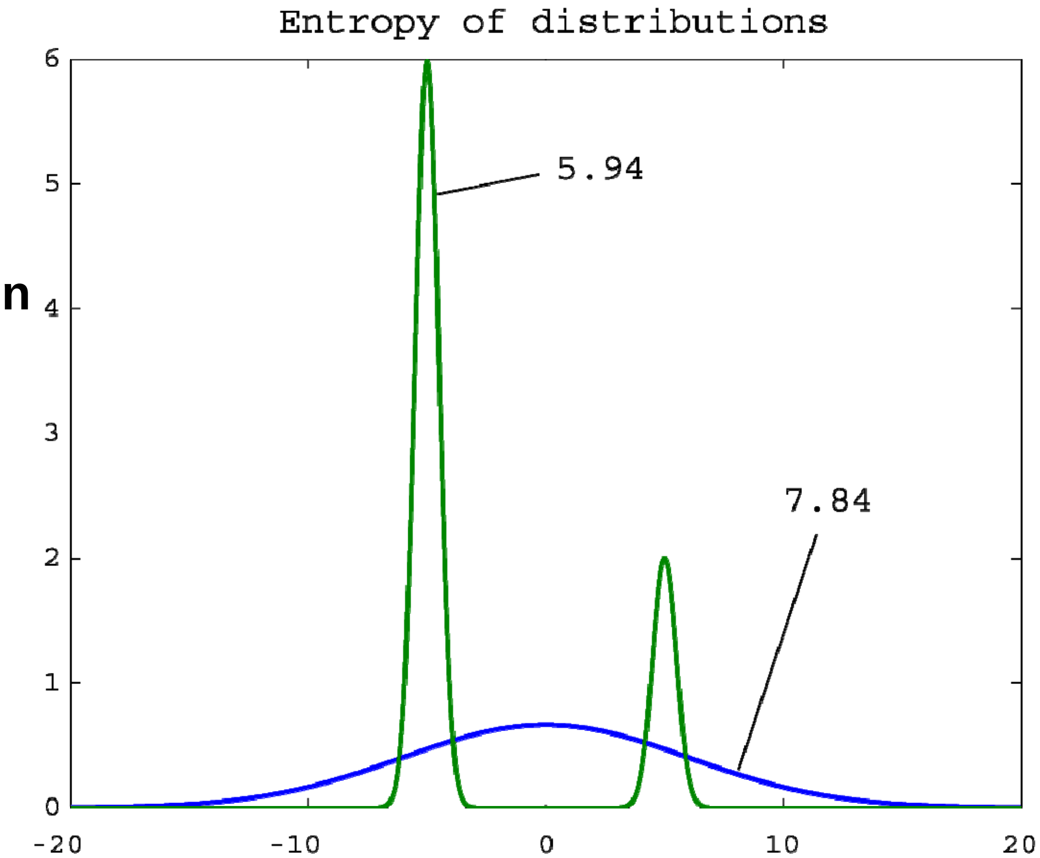
"entropy of echo power (scatter) distribution"

- more highly localized distribution has less entropy (in case of a constant integral value)

information entropy *(H)*

$$H = \int P(x) \log P(x) dx$$

P(x) **: range power distribution**



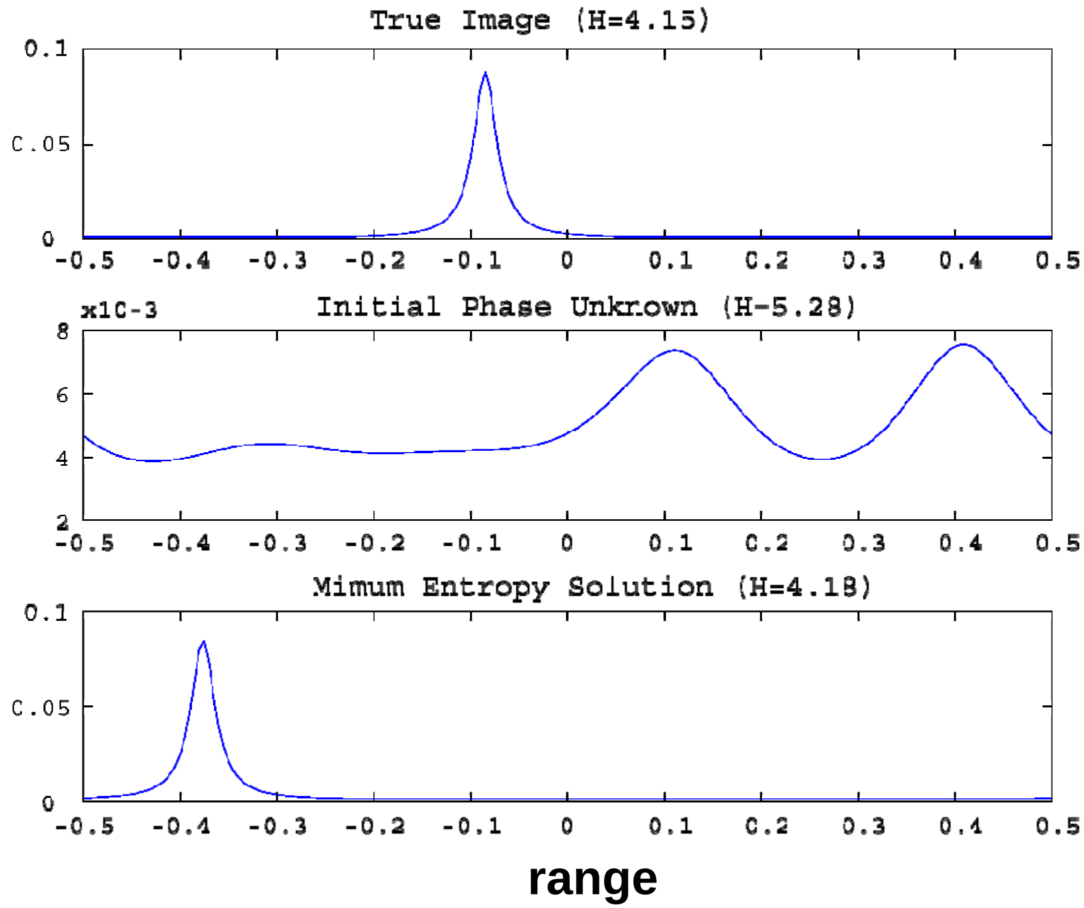
minimum entropy solution of unknown eigen (initial) phases

- determinable except relative range offset (which does no effects on entropy)

known eigen phases (true image)

random solution (ignore eigen phases)

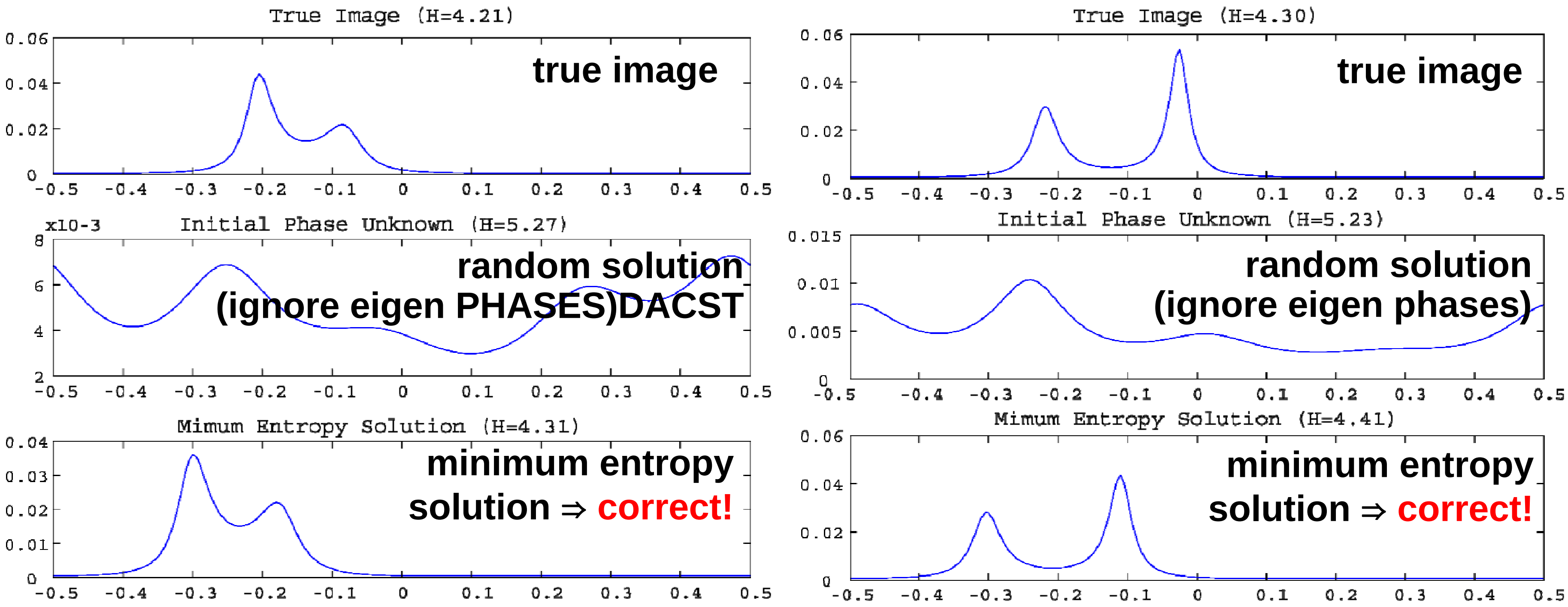
minimum entropy solution
⇒ correct solution!
except relative range offset



minimum entropy solution of unknown eigen (initial) phases

- even in case that multiple targets exist, this method provides correct solutions

There exists no mathematical proof of its uniqness of the solution yet! but we believe so!;-)



FDI "initial phase" determination

- Again, there are no reason that propagation paths are always constant and then initial phases does not change over time especially for further ranges... (but FDI will work if relative initial phase differences among FDI frequencies are preserved, but still relative range offset might vary with time.)
- So trying "minimum entropy" method might be valuable at least to determine initial phase at a certain time (assuming the method always gives us correct distribution..).
- To confirm whether FDI works well or not, ...
- 1) to check whether the results from both stereo radar channels are the same or consistent
- 2) to compare results assuming that relative initial phase differences are preserved, with results with all initial phases are determined by the "minimum entropy" method at every time (FDI integ periods) (range offset must be set for each time).

FDI results

min.entropy applied for each (all the) time independently
(range offset for t+Δt is determined from one for t)

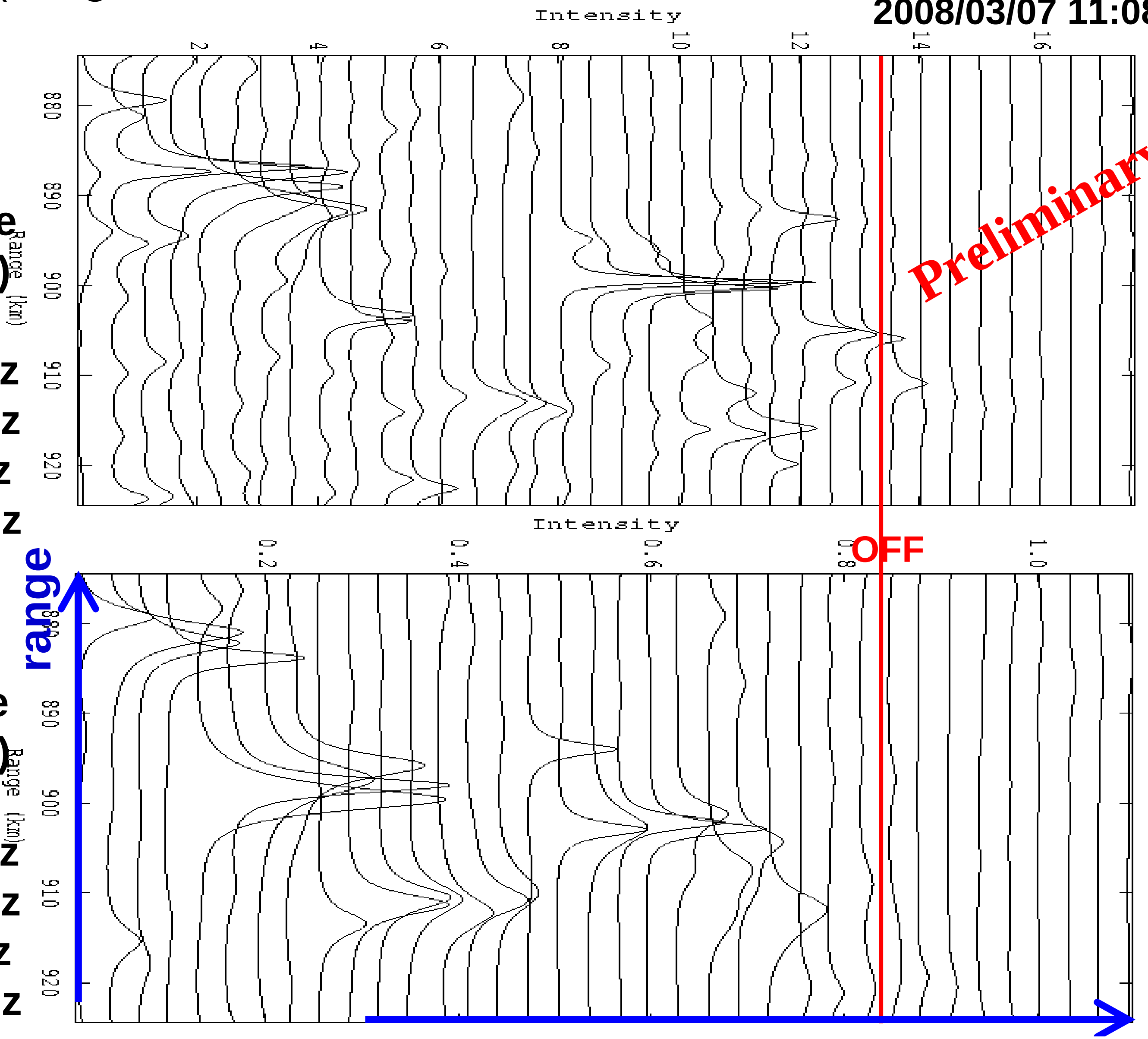
2008/03/07 11:08-11:09

chA

double pulse
r=60(900km)
5-frq FDI
F1=16560kHz
Δf=3,3,9,9kHz
minΔf= 3kHz
maxΔf=24kHz

chB

single pulse
r=60(900km)
5-frq FDI
F1=16595kHz
Δf=3,3,3,3kHz
minΔf= 3kHz
maxΔf=12kHz



3000km=20ms
~25ms/seq
(7pulses:~90ms:
:~4 times)
5-frqFDI
(5data/FDI)
~130ms/FDI
7~8FDI/sec
1FDIimage=
10FDIseq=
50data/~1.3s

Summary this time (1/2)

- A new code for Single- (and double-) pulse TMS mode with multi-frequency FDI was developed and tested to improve or investigate temporal resolution of range imaging by FDI method. (The resolution was improved from 5-sec to ~1.5sec per image.)
- FDI range imaging analysis requires determination of "initial phase" to get proper results in principle (<=> SDI not).
- The "initial phase" determination is sometimes or often fairly difficult for far range echo analysis most possibly due to fading effects (or different or multiple ray paths for different frequencies and their temporal variation).
- In fact, Dynamic Doppler Power Spectrum and temporal echo power variation for several close FDI frequencies (~kHz) show sometimes very different behaviors, suggesting the existence of the fading effects – never non-negligible for investigating finer structure than ever... (BE CAREFUL!!;-)

Summary this time (2/2)

- "Minimum entropy" method is tried to be applied to determine the "initial phases" of artificial FAIs at a far range (except absolute initial range offset) (though its uniqueness of the solution and the mathematical or physical truth is not proved).
- FDI results from both stereo channels using "minimum entropy" method seem to be relatively consistent (more fine tuning will be required at this stage) and thus it seems to work even when other trial fails is suspicious.
- Still work in progress..., more detailed comparison will be continued hopefully...
- For range imaging for ionospheric far range echoes, pulse/phase coding might be more promising though additional radio authority license issues might arise. (c.f. FDI nees no cost (only software), no additional hardware, and no additional license, and highest resolution could be expected if S/N ratio is enough high. so it'll be good if it works well.)

Many thanks...!

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The End

Editors note: this PDF does not fully represent all aspects of the presentation,
to better appreciate this work it is recommended that the full presentation be viewed.