H20(2008)年度名古屋大学太陽地球環境研究所研究集会「中緯度短波レーダー研究会」
名古屋大学東山キャンパス野依記念学術交流館会議室（愛知県名古屋市千種区不老町） 2008.12.08

SuperDARNによるイメージング観測

SuperDARN imaging radar status

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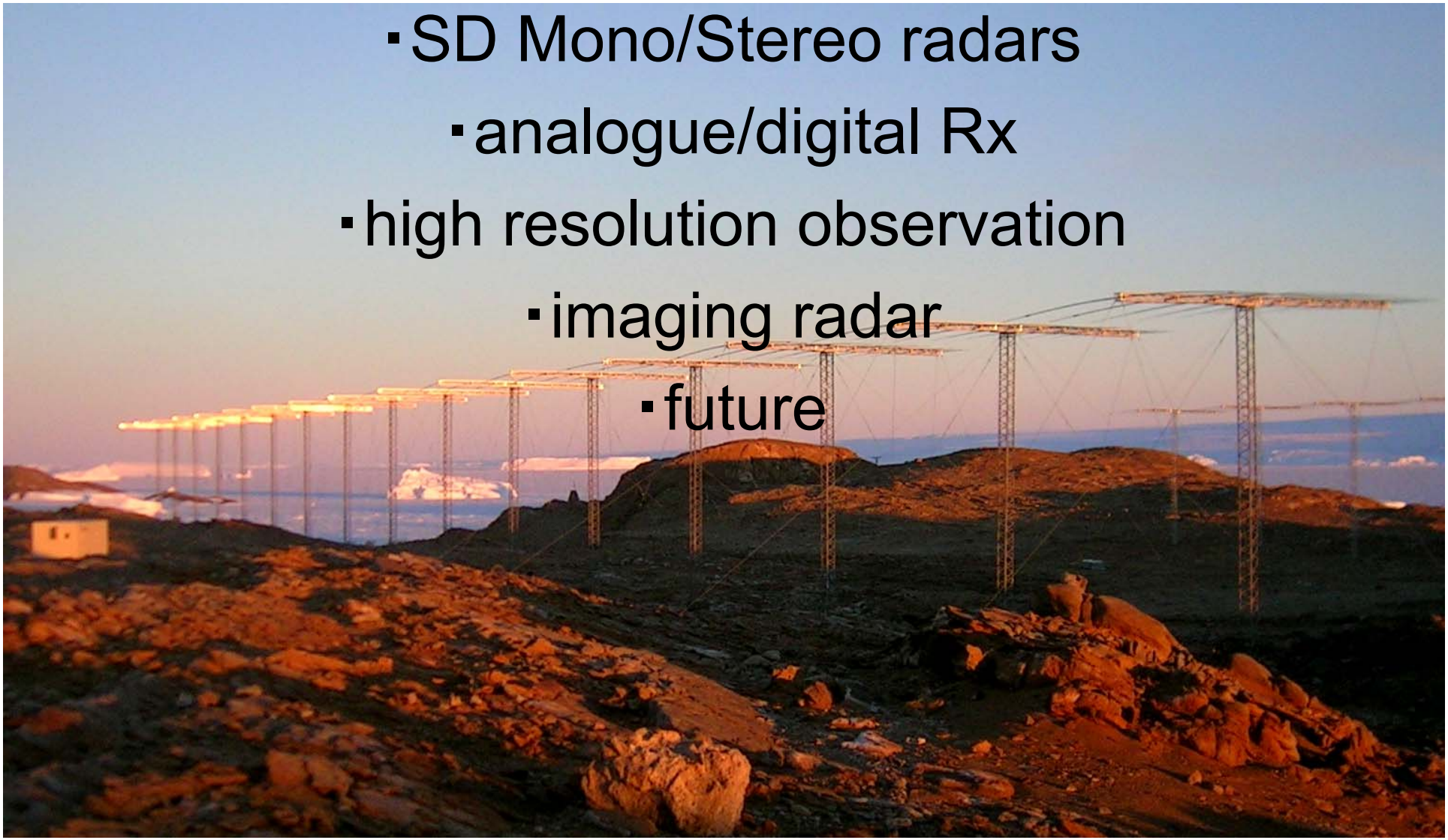
NIPR/ROIS/SOKENDAI, Tokyo,
Univ. of Leicester, UK

SuperDARNによるイメージング観測

概要

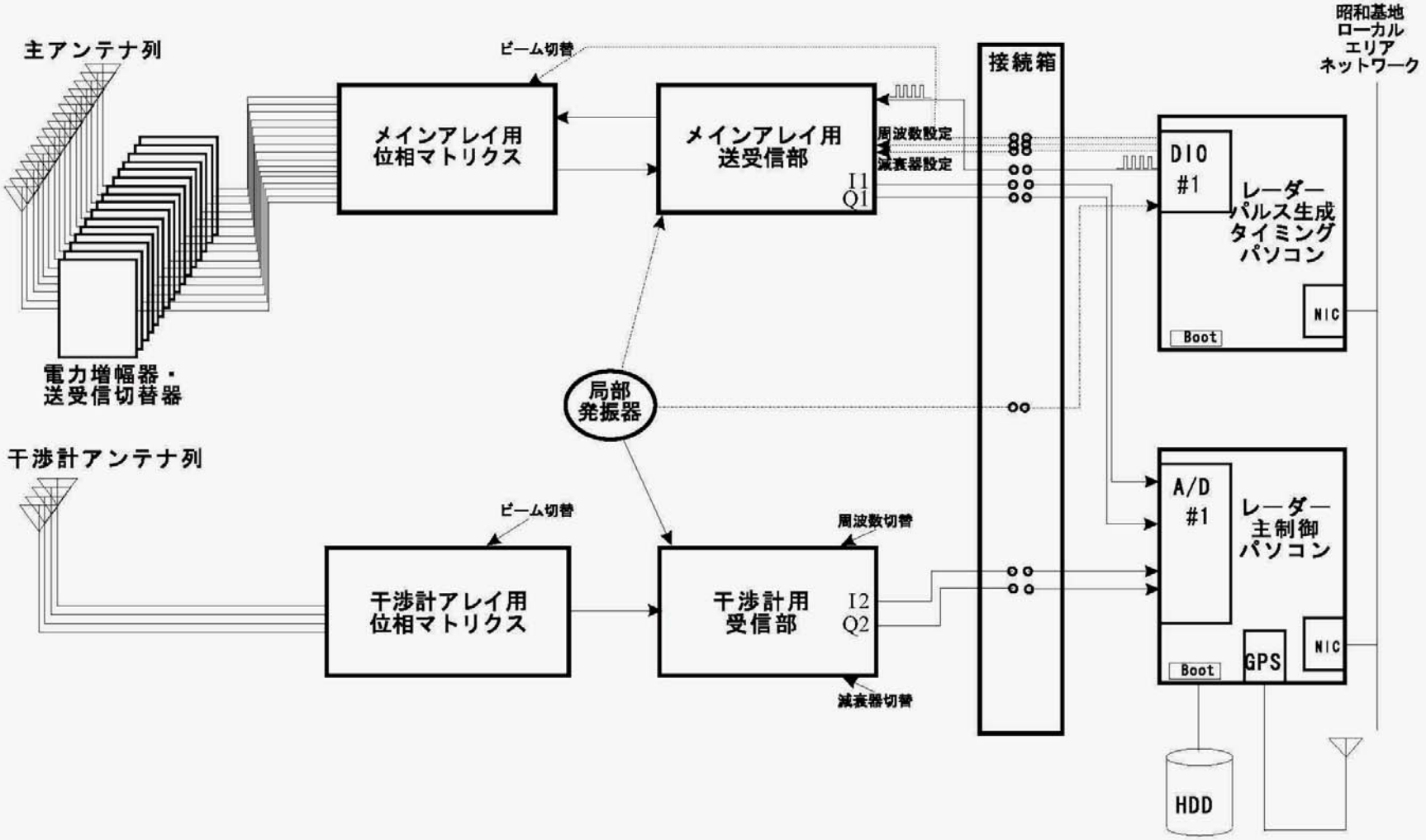


SuperDARN

SD mono/stereo radars

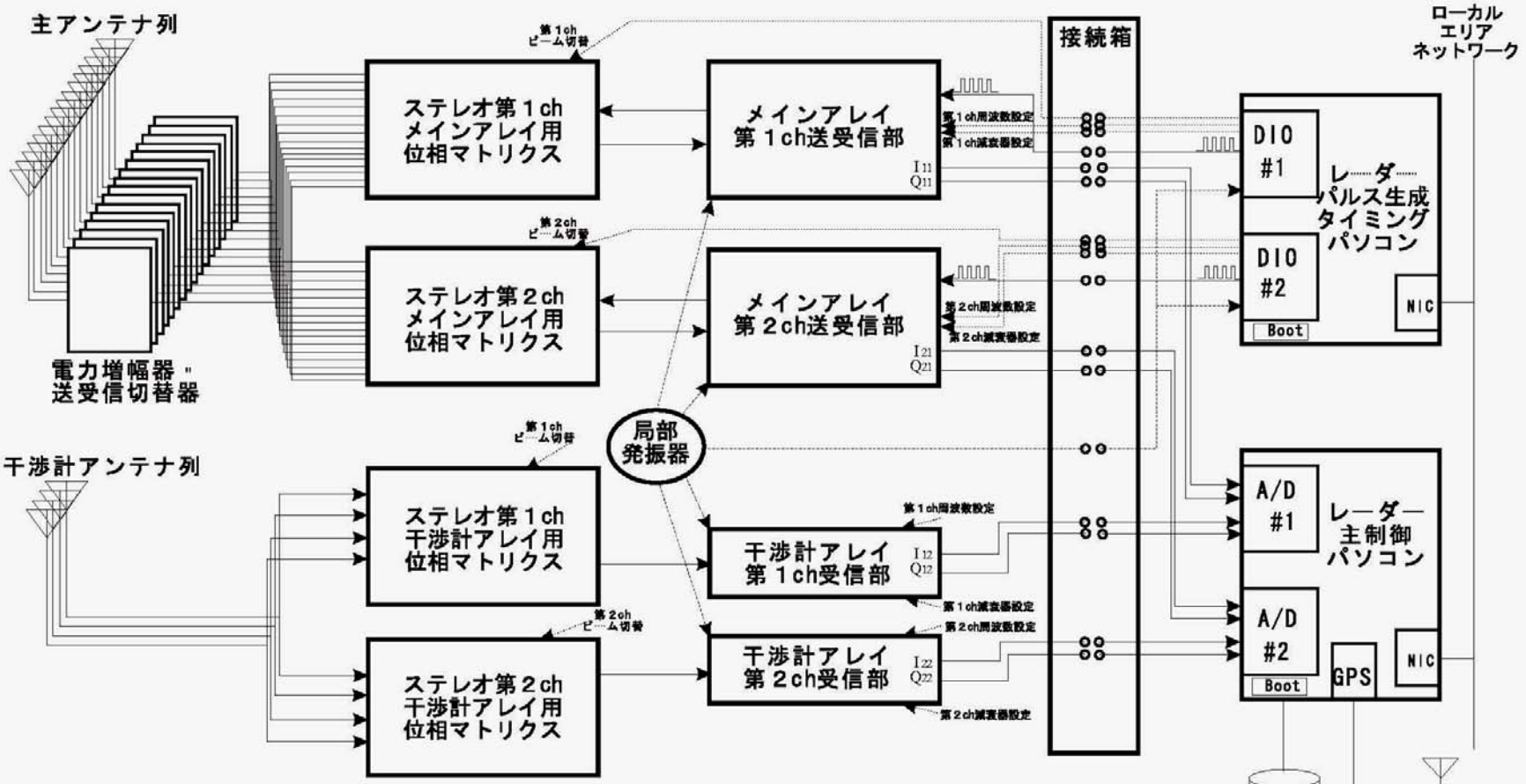
SD conventional (mono) radars

- Each Tx(PA) has enough duty cycle capacity



SD stereo radars

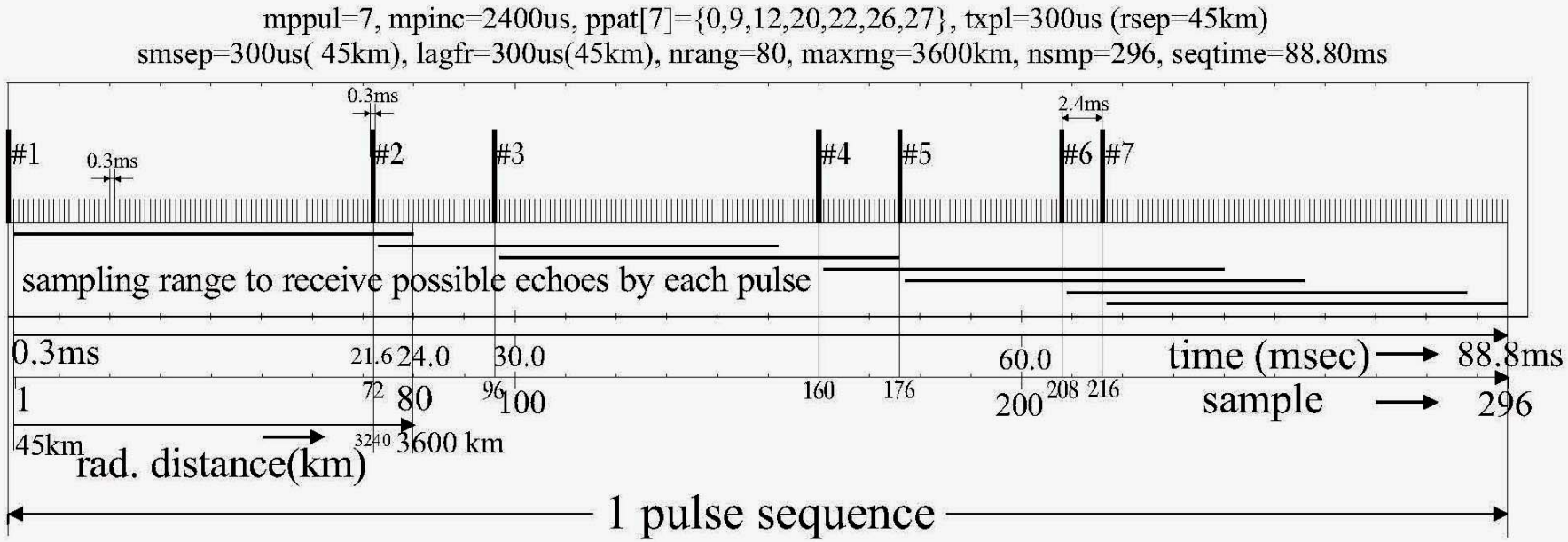
- 1 radar acts as 2 (mostly) independent radars



indep. : beam, txpl, smsep, pulse pat, frang, nrang etc.
common pulse seq & intt periods dep. on software

SD conventional (mono) radars

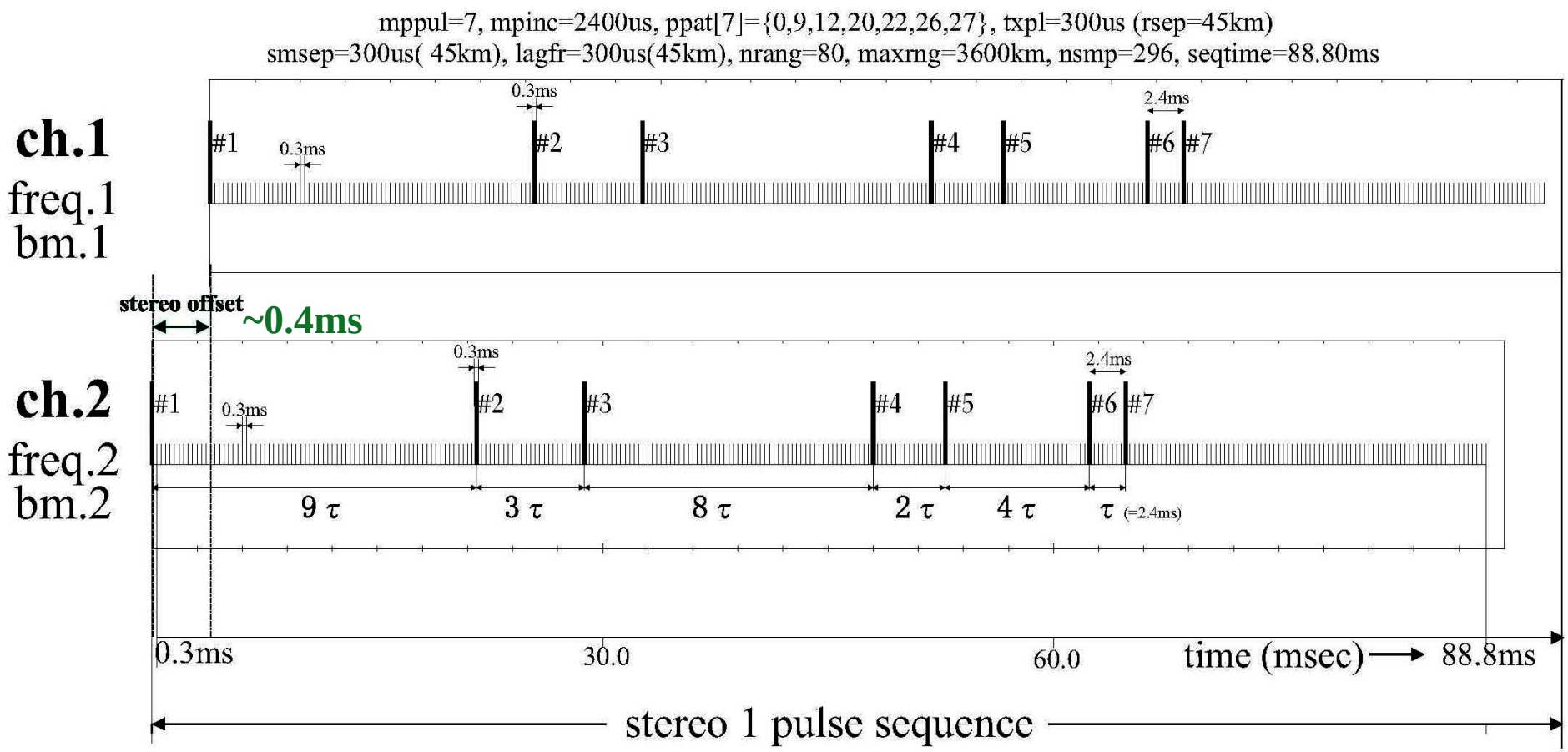
SuperDARN 短波レーダー
パルスパターン（パルス系列）
及びサンプリングタイミング（例）



~0.1s

SD stereo radars

SuperDARN 短波レーダー(ステレオモード)
パルスパターン（パルス系列)
及びサンプリングタイミング （例）



~0.1s

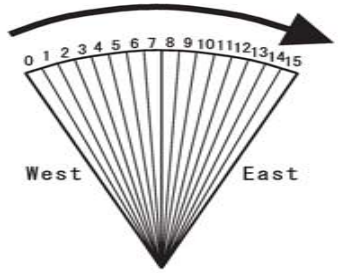
ステレオSuperDARN短波レーダーシステム

これまでのレーダー単体では特定単一の観測モードしか同時に実行できない

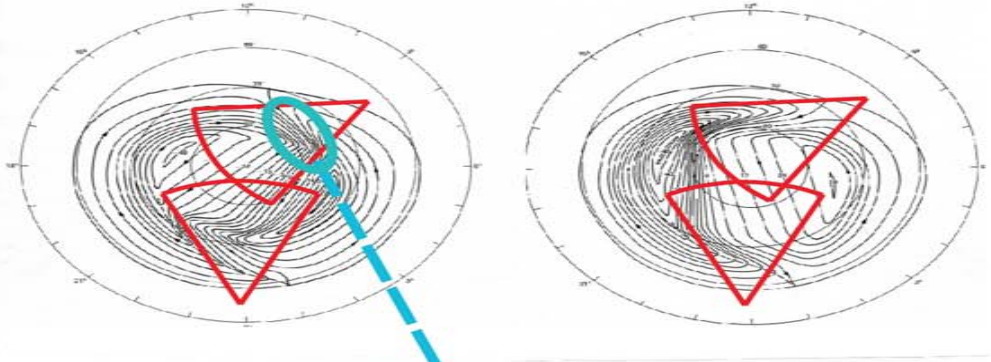
多様且つ複雑な極域大気圏現象の真の理解・解明の為には
- **大域的電離層対流の背景場**とその変動の取得
- **磁気圏領域へのマッピング**（個々の現象の大域対流中での位置付け）
- **高時間・高空間分解能観測**による詳細な物理素過程の解明

の**すべてを同時に**行うことが肝要。

大型短波レーダー観測視野

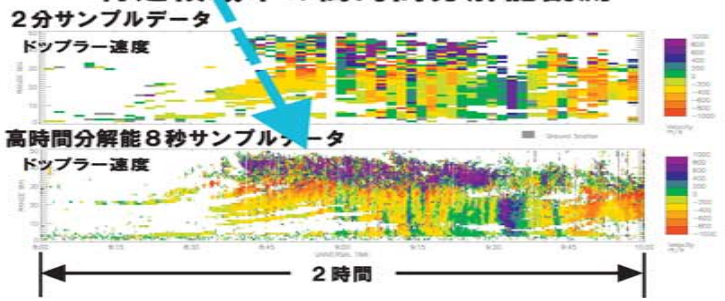


大域的電離層対流と短波レーダー観測視野



大型短波レーダー

特定領域中の高時間分解能観測



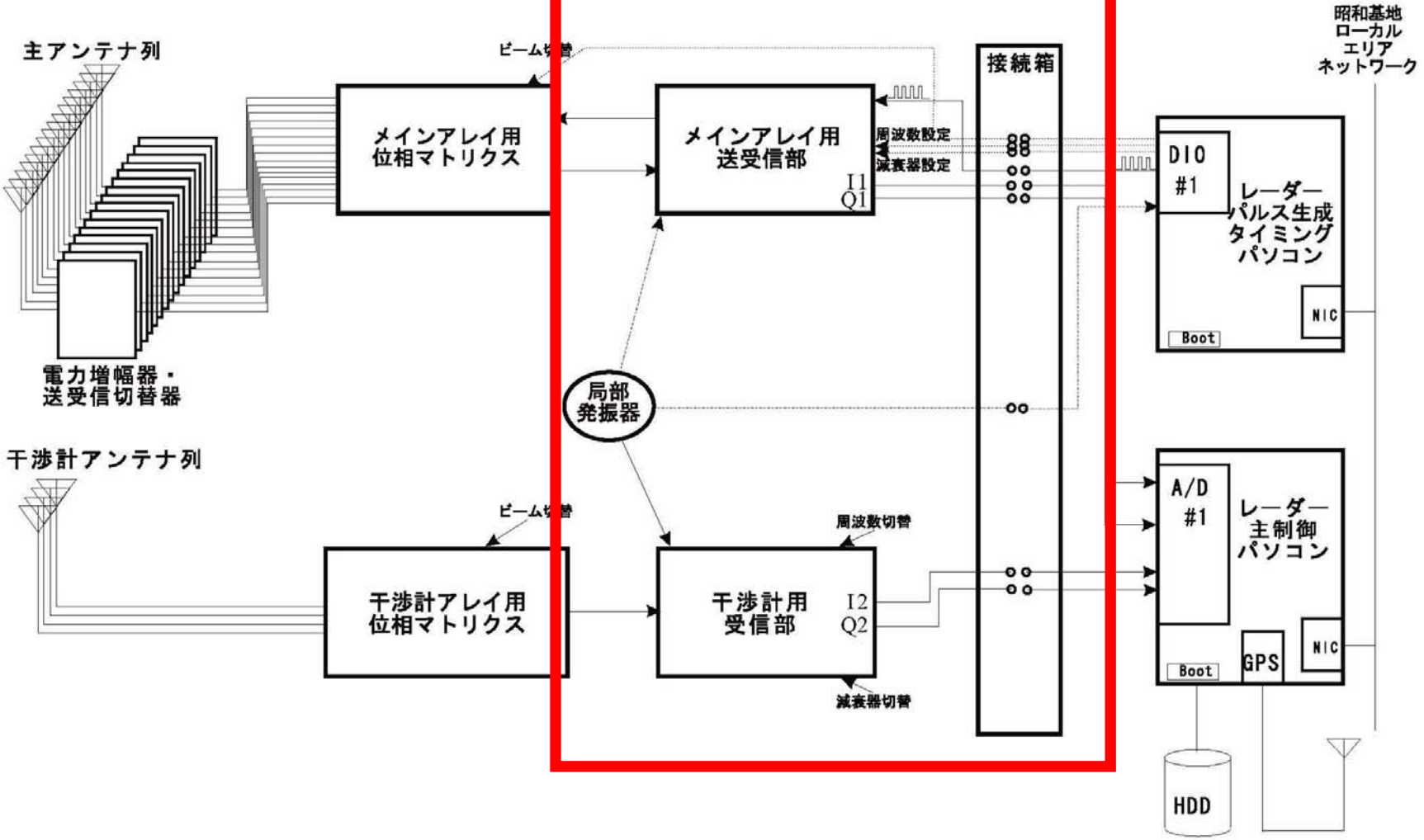
ステレオシステムなら1台のレーダーで**2台分**の働き

大域的電離層対流観測と高空間・高時間分解能観測の両立等、
多様なレーダー観測モードの同時実行が可能
SuperDARNスケジュールと独立した自由な観測が可能

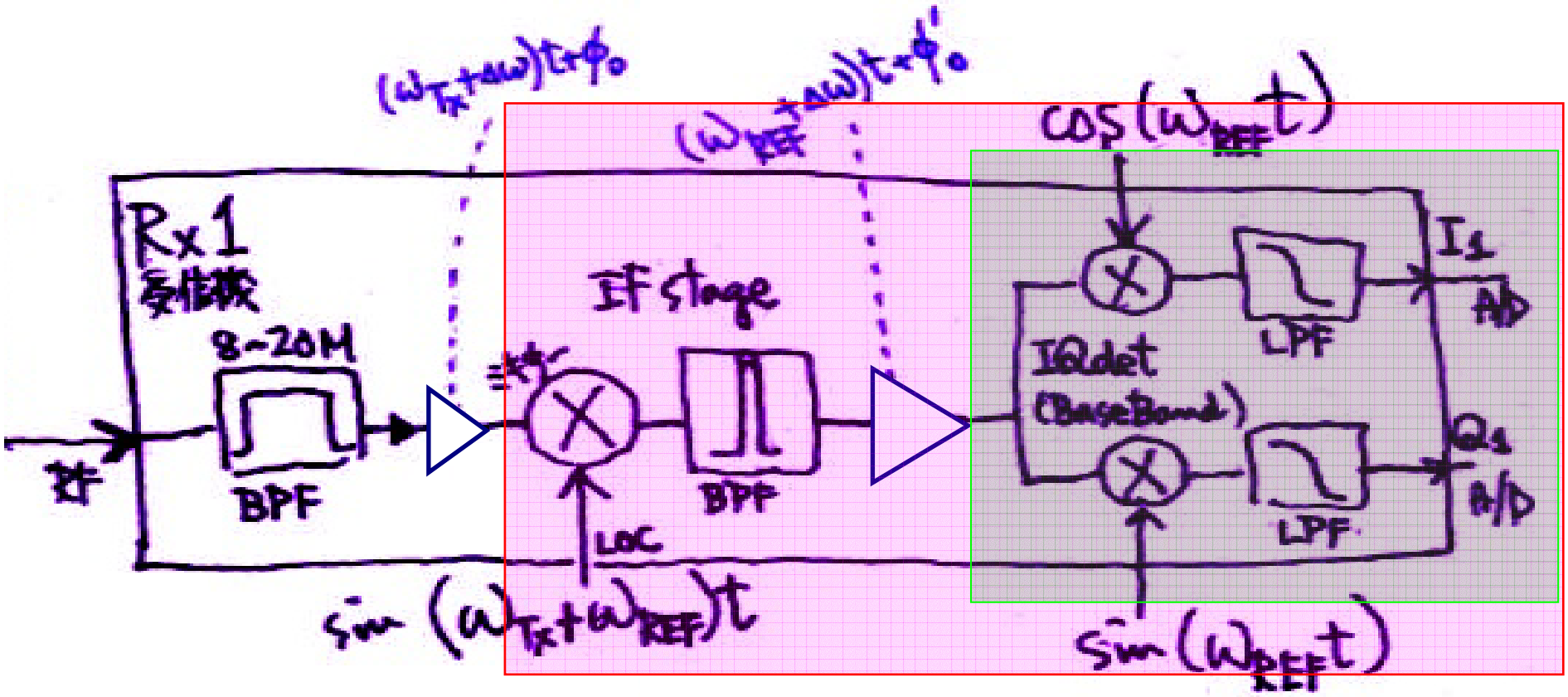
SuperDARN

SD analogue/digital Rx

SuperDARN 短波レーダーシステム

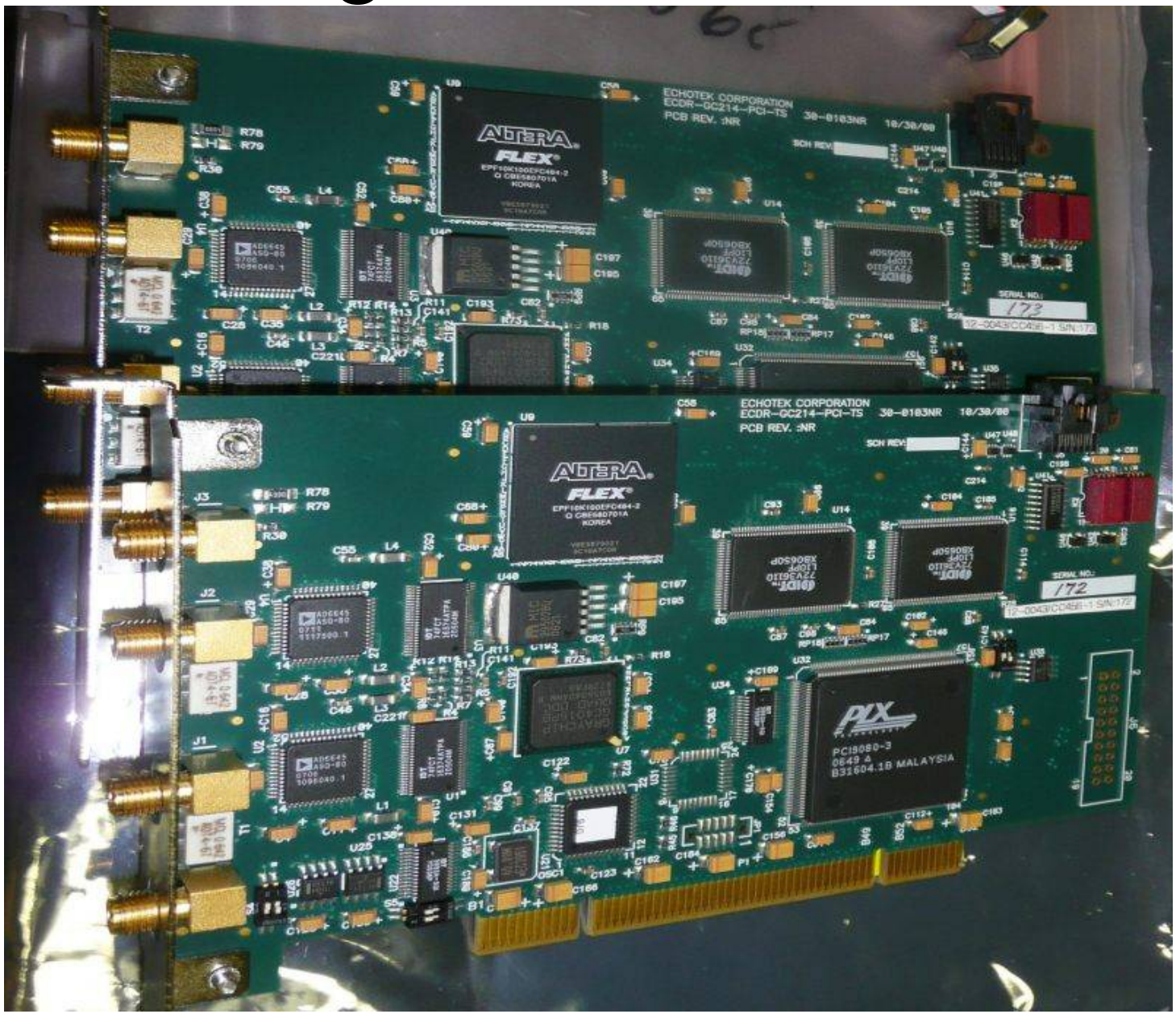


analogue to digital Rx system



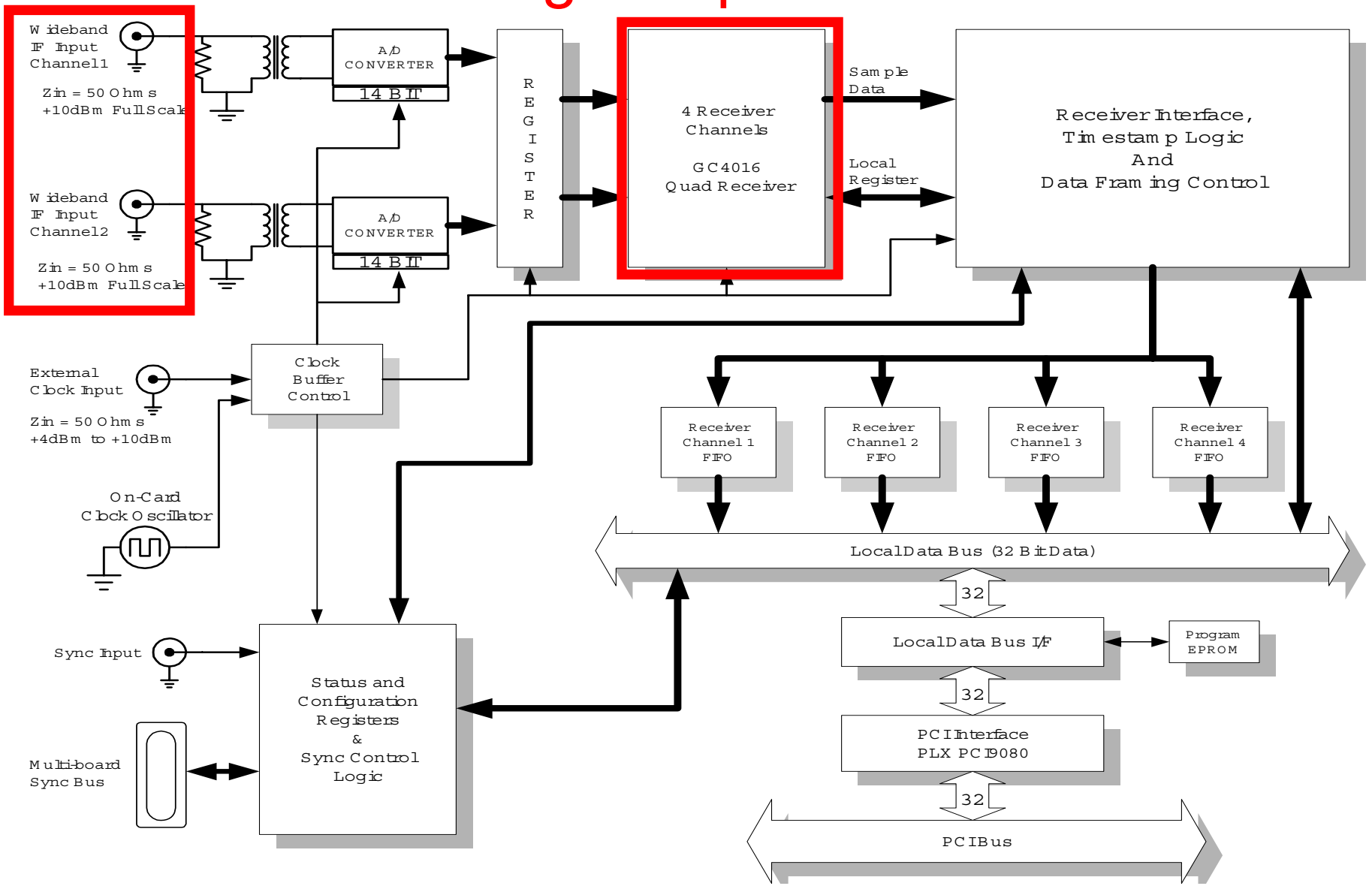
replace by digital Rx...

digital Rx cards



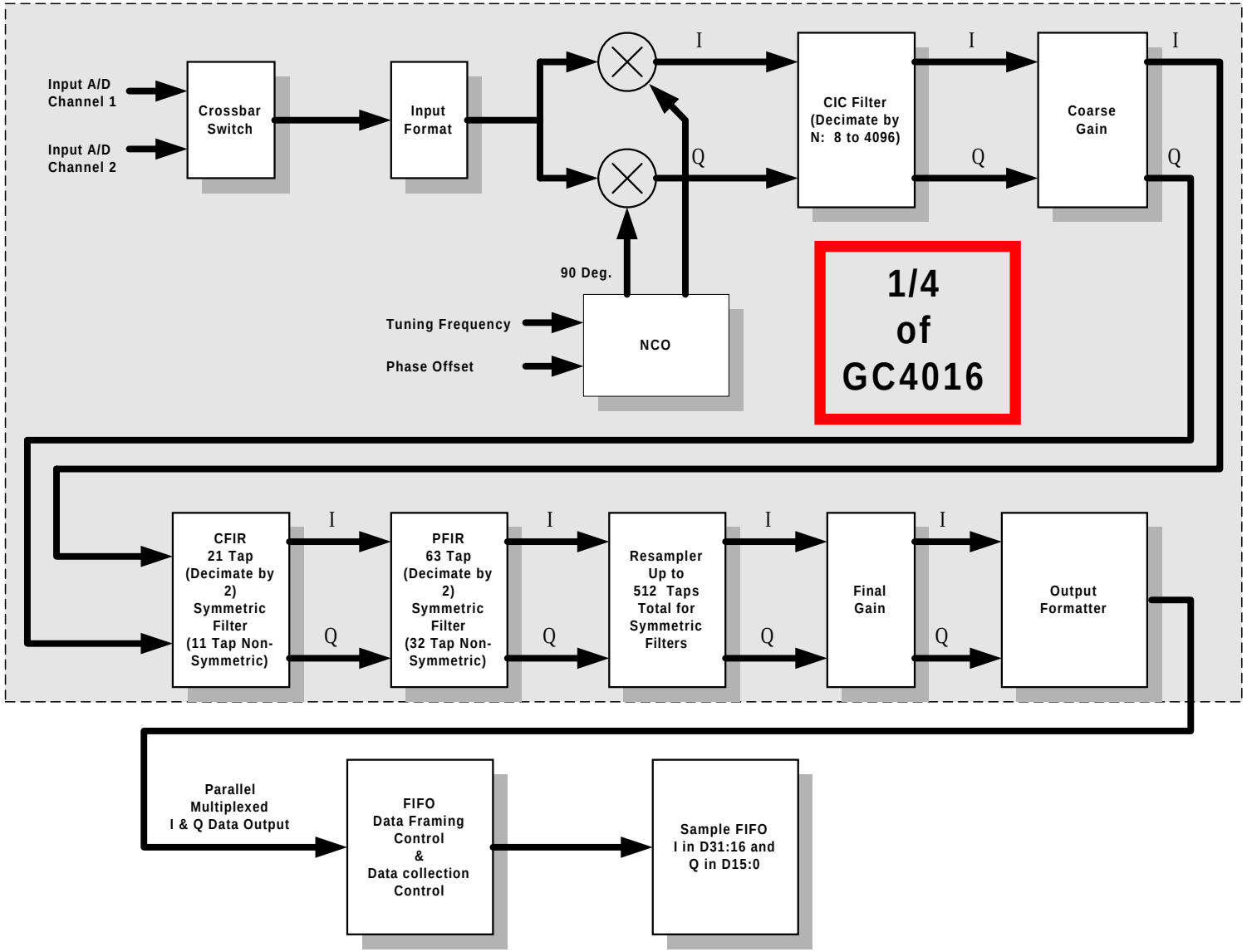
ECDR-GC214-PCI/TS-80

2 analogue input channels



GC4016 on GC214-PCI/TS-80

each AI connects to 4 digital Rx channels



Digital Rxは、under-samplingを利用

SHANNON'S INFORMATION THEOREM AND NYQUIST'S CRITERIA

- Shannon:
  - An Analog Signal with a *Bandwidth* of f_a Must be Sampled at a Rate of $f_s > 2f_a$ in Order to Avoid the Loss of Information.
  - The signal bandwidth may extend from DC to f_a (*Baseband Sampling*) or from f_1 to f_2, where $f_a = f_2 - f_1$ (*Undersampling, Bandpass Sampling, Harmonic Sampling, Super-Nyquist*)
- Nyquist:
  - If $f_s < 2f_a$, then a Phenomena Called *Aliasing* Will Occur.
  - Aliasing is used to advantage in undersampling applications.

デジタル受信機の利点

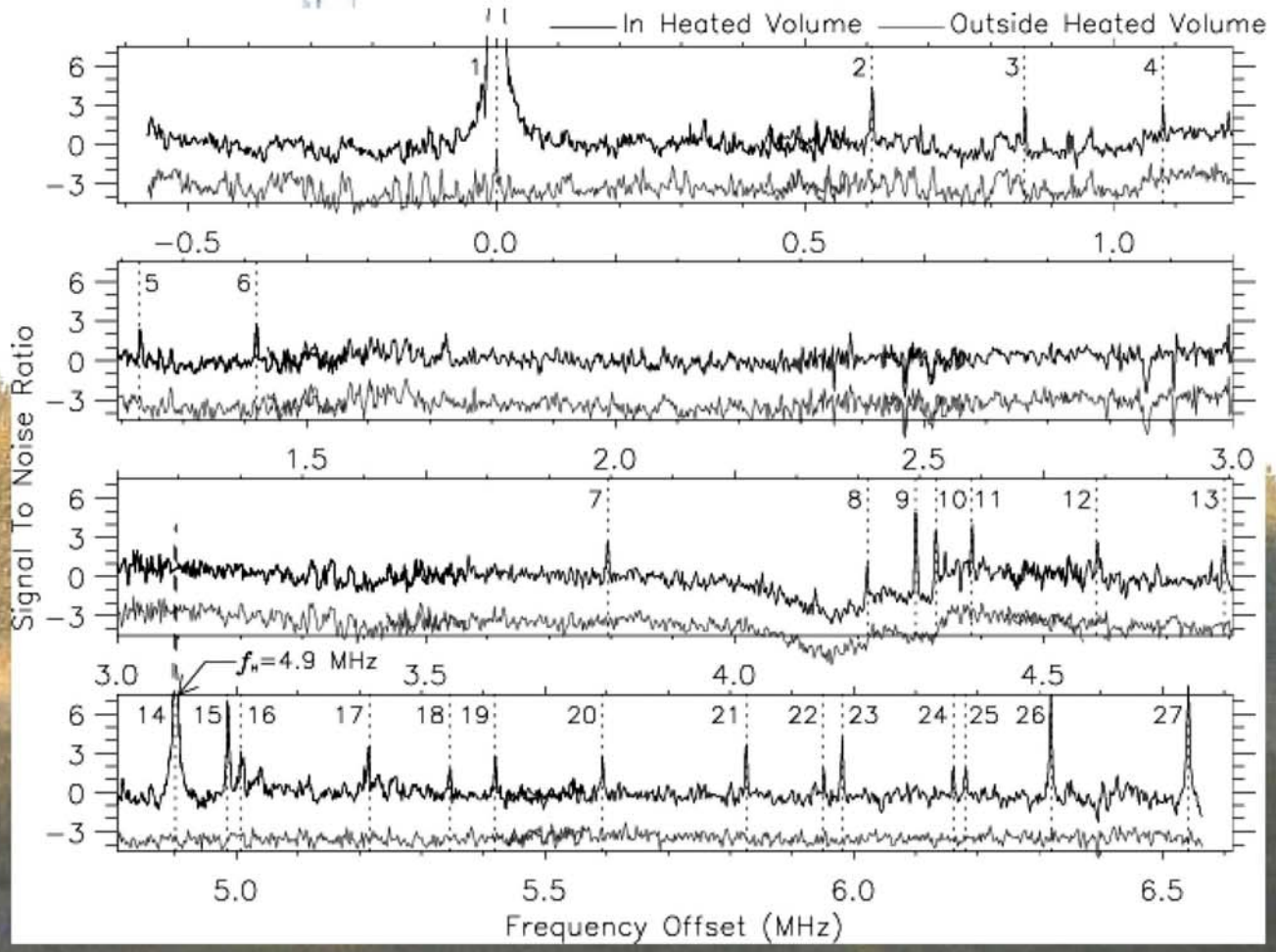
- 安価?（前処理(front end)必要なので、結局は。。）
- 検波段のDC offsetが発生しない！
- BPFをsoftwareで任意に設定可能！（重要）
  （new fclr/pulse coding等に必須）
- 受信周波数も任意に設定可能(new possibility)
  （FreqTxとFreqRxは同じでなくてもよい。）
- 1RF入力に対し複数(3-4)受信機を内蔵
  （Stereo化/同一TxFreqに別処理等可）
- 高速sampling (≧MHz)可能（cf. ISA-AD:10kHz）
  （但し、送信帯域狭のままでは独立ではない。）
- compact
- no more analogue engineering effort (except front ends...)

⇒安定動作・保守性向上、観測自由度の増大

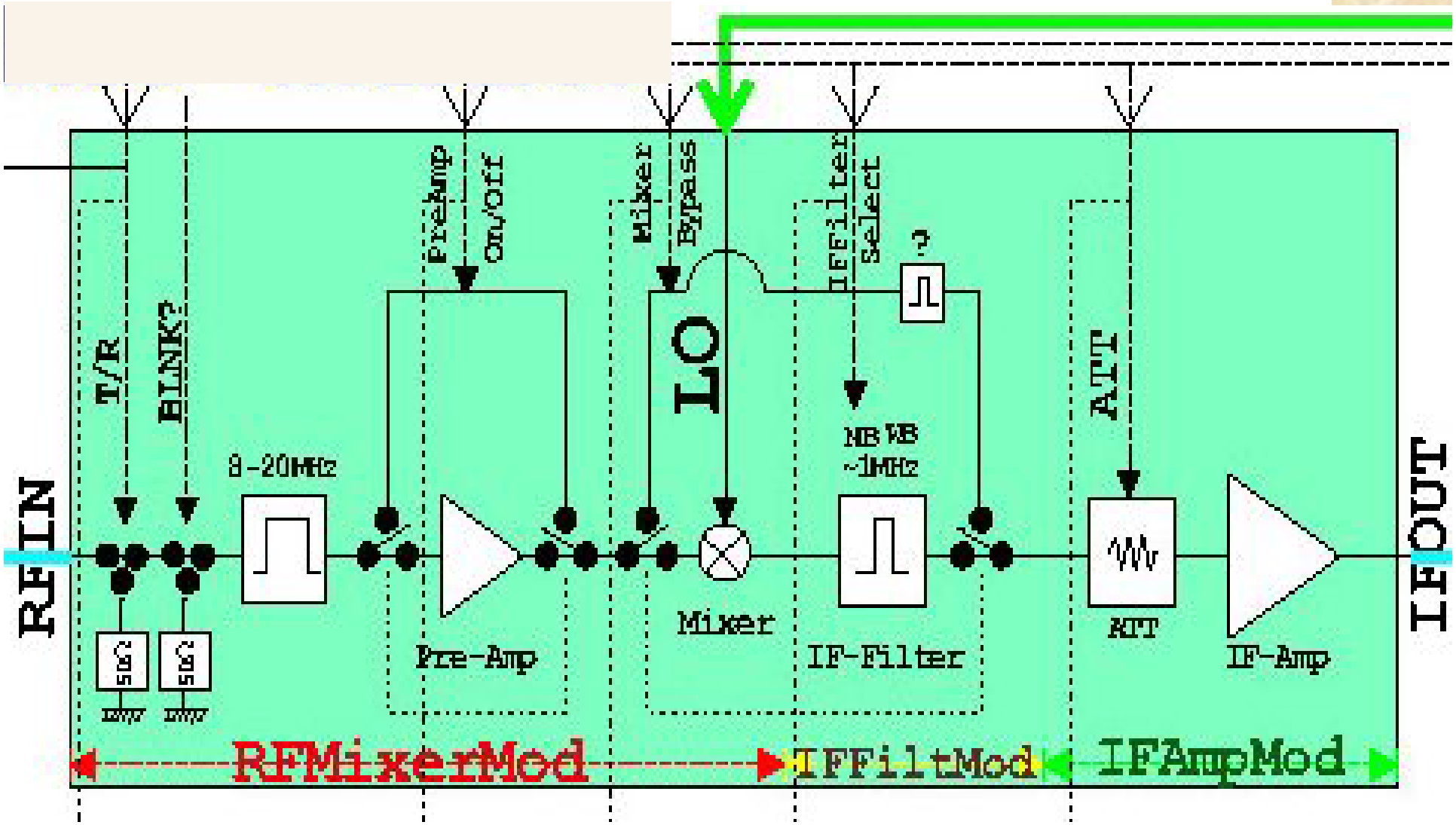
(但し、software/hardwareの知識・熟練必要to do something new)

GEOPHYSICAL INSTITUTE

New Science

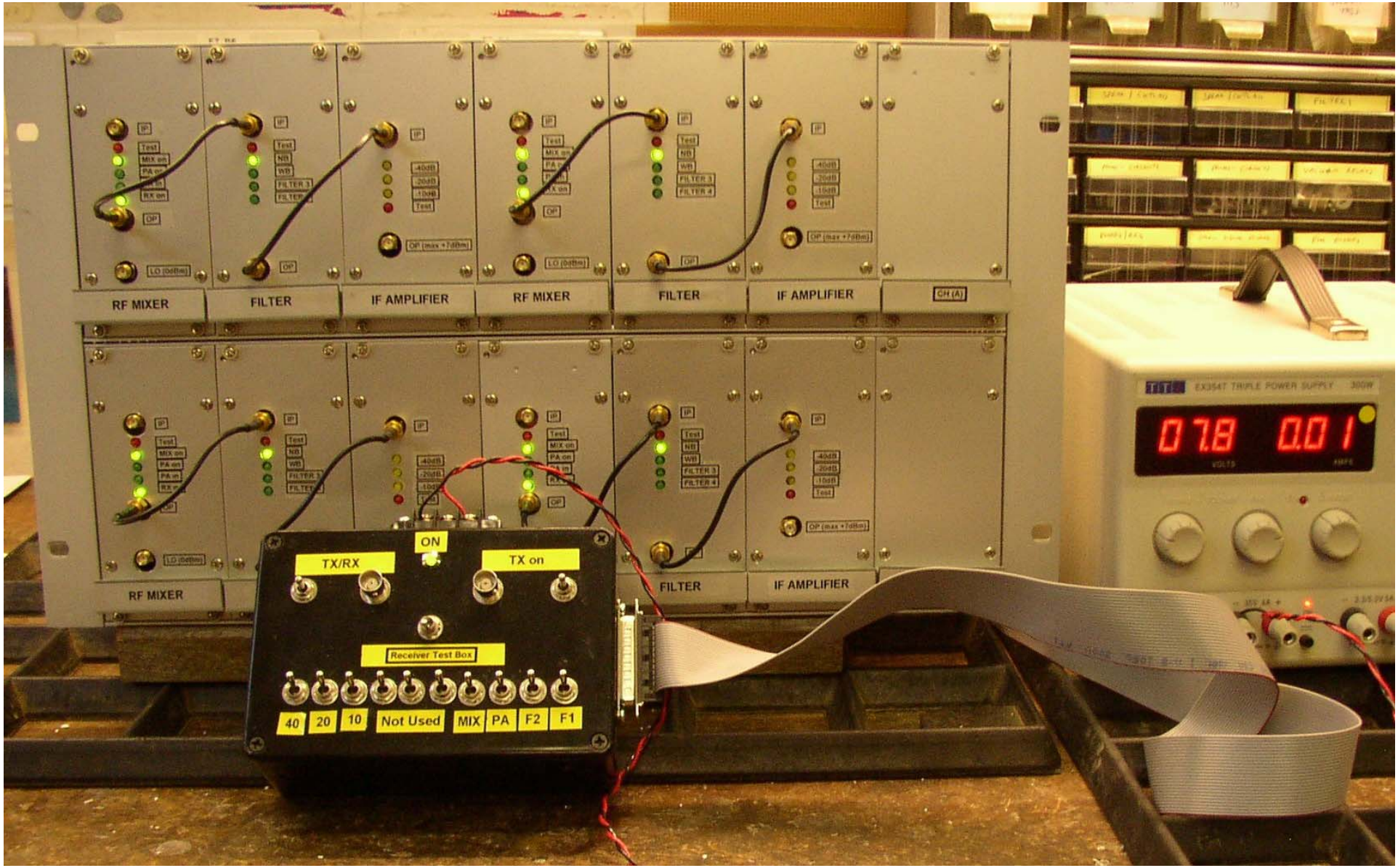


Digital Rx front ends (DRFE)



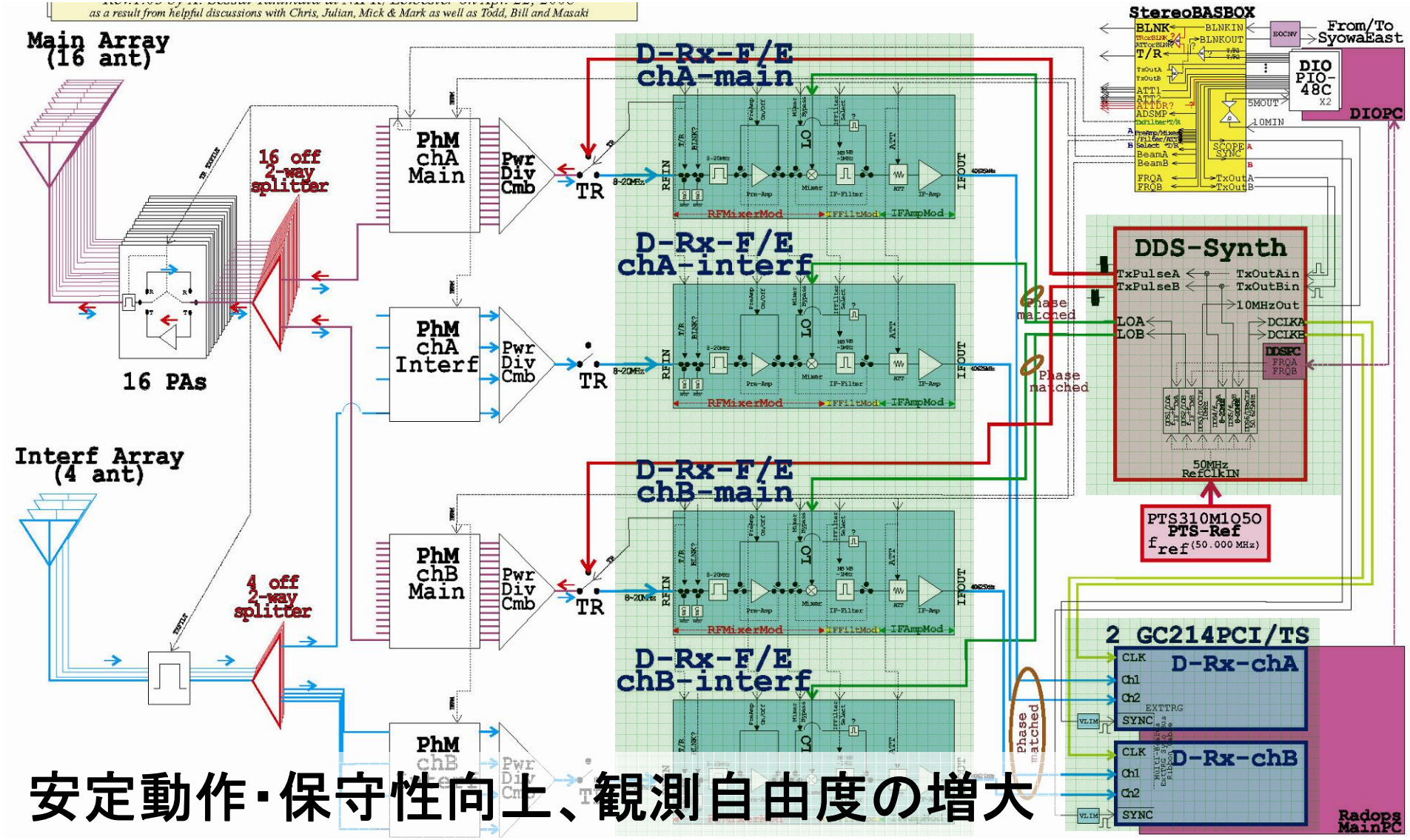
受信機系動作確認

w/ SG/DDS and Oscilloscope / Spectrum analyzer



短波レーダーの一部更新と保守

- デジタル受信機系への移行はほぼ完了（HF1,49次）



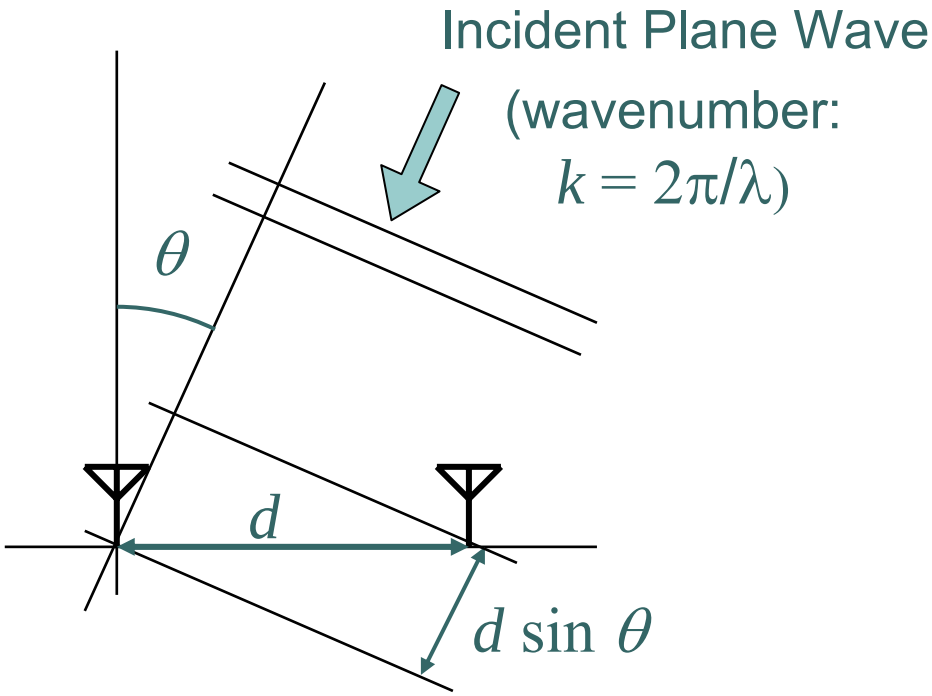
安定動作・保守性向上、観測自由度の増大

SuperDARNによるイメージング観測

SuperDARN to imaging (SDI) radar

Basic Radio Interferometer (narrow band representation)

- Two-antenna Model



Phase difference:

$$\psi = kd \sin \theta$$

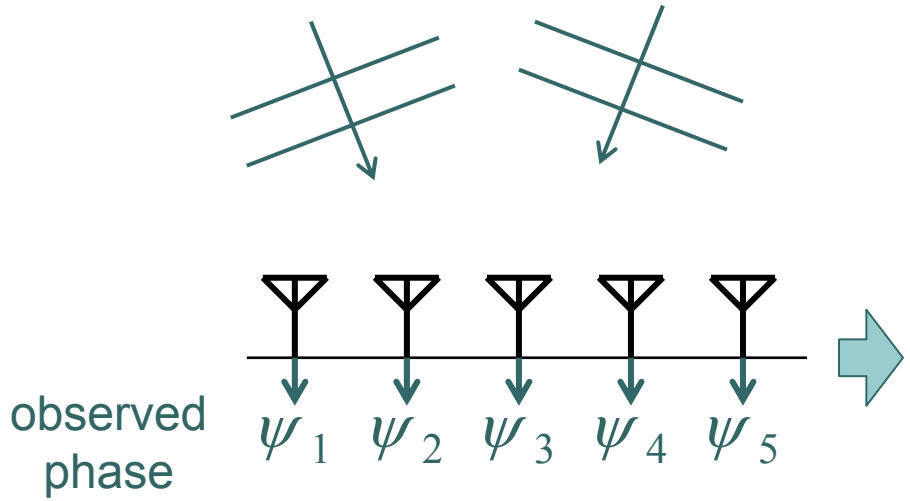
Angle of Arrival

$$\theta = \sin^{-1}(\psi / kd)$$

under the condition of $d<\lambda/2$

Basic Radio Interferometer (narrow band representation)

- Multiple (more than two) antenna Model



How can we estimate input signals?

Estimation Scheme

(1)Parametric Point Source Model

Eigen Value Decomposition (MUSIC, ESPRIT etc...)

(2) Non-Parametric Distribution

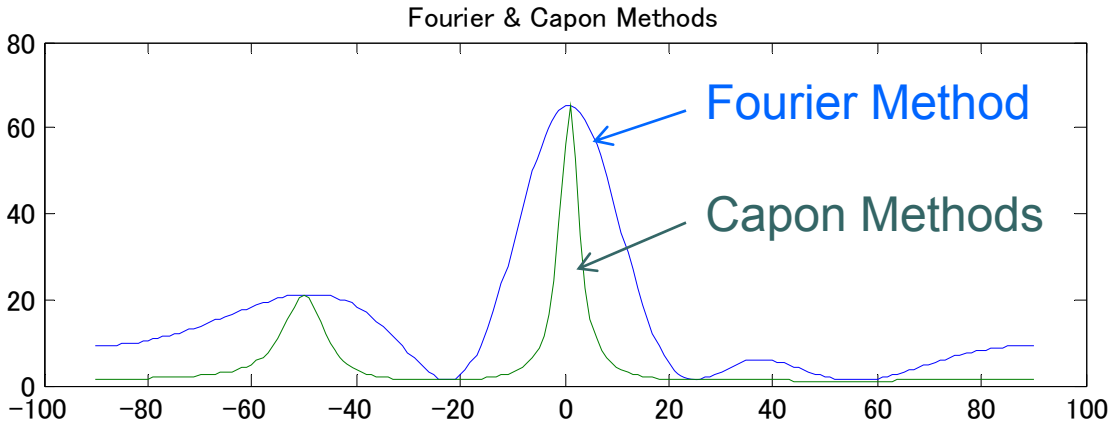
Capon Method

LG Method

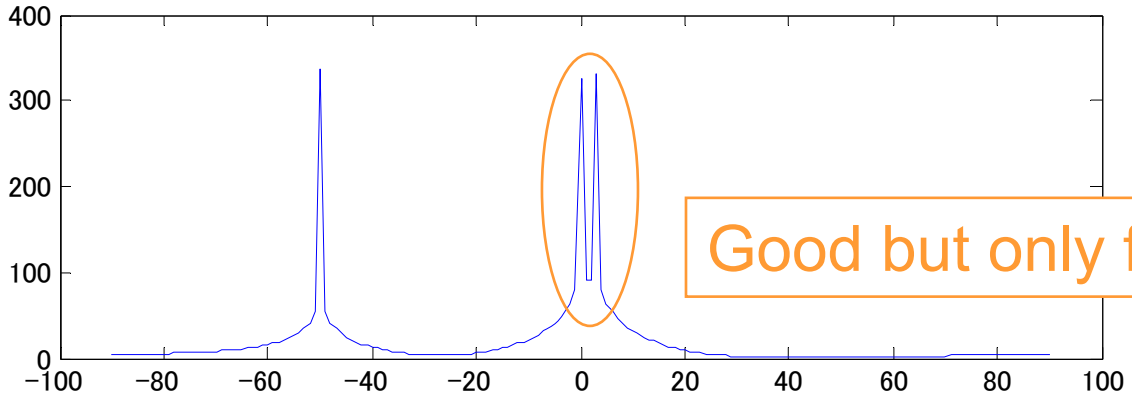
etc...

Examples of Estimation Schemes

- Capon and MUSIC Methods



MUSIC (=Multiple Signal Classification) Method

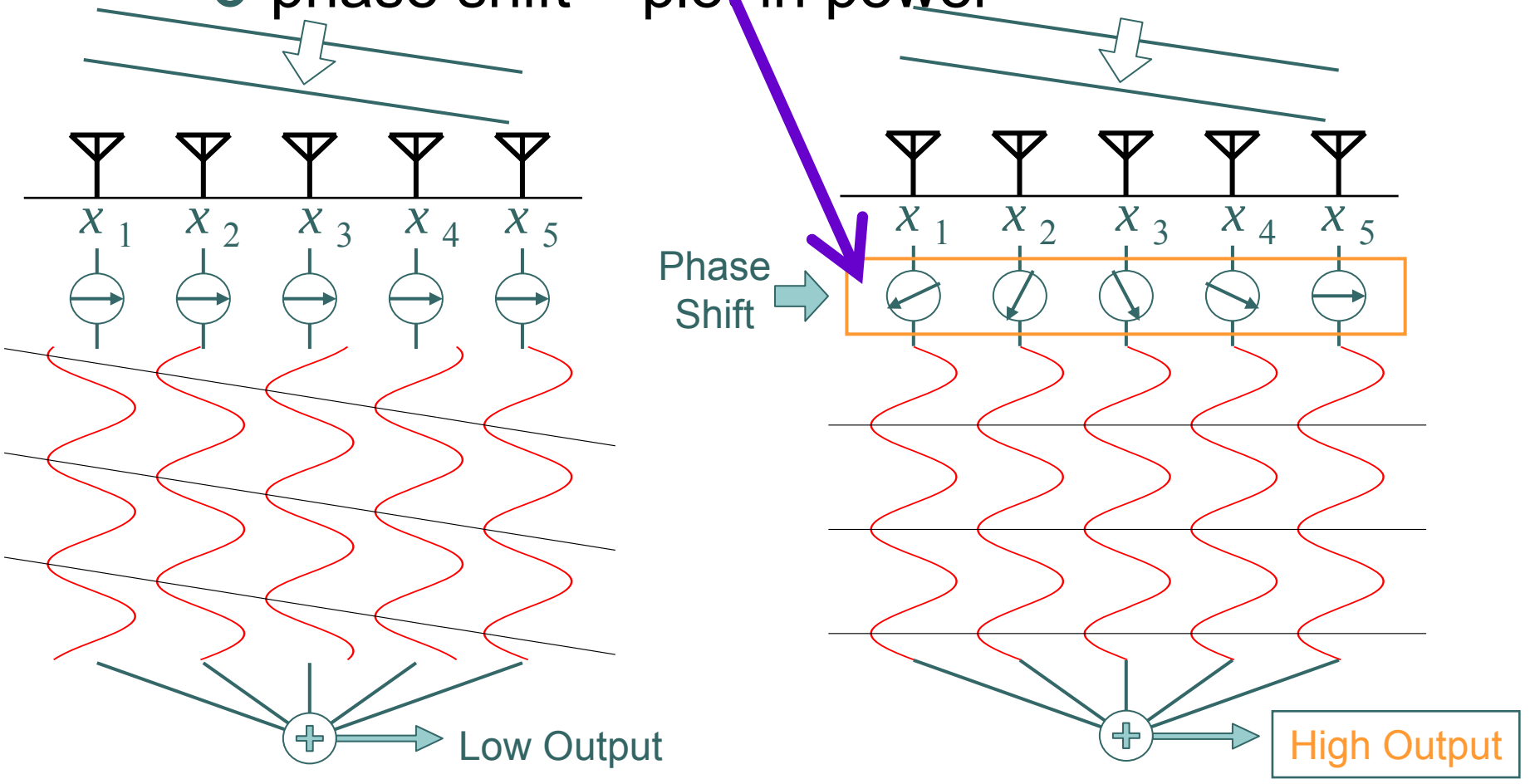


Good but only for point estimation

Spatial Domain Interferometer(beam forming)

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

- phase shift + plot in power



Fourier Method

Power Distribution by Fourier Method

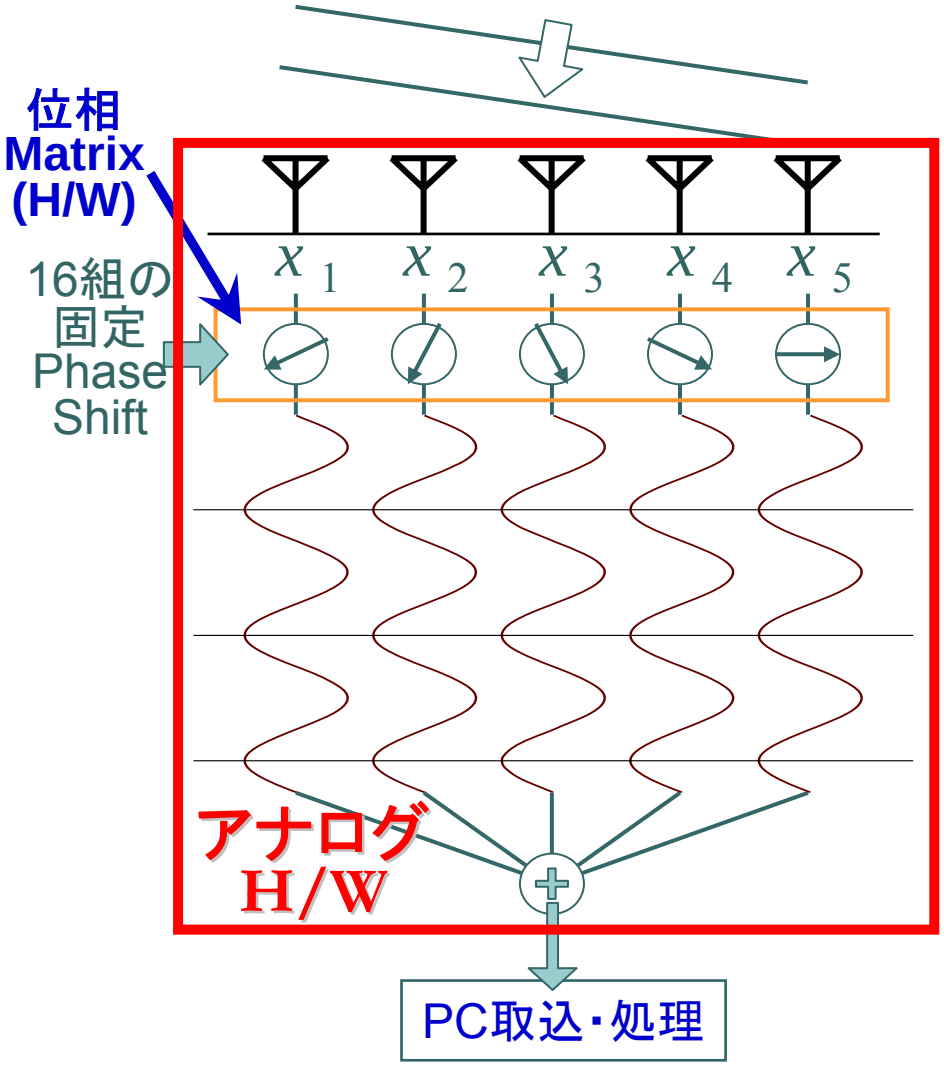
$$
\begin{aligned}
P(\theta) &= \left\langle \left| \sum_i \exp(-\mathrm{i}kd_i \sin\theta) x_i(t) \right|^2 \right\rangle \\
&= \left\langle \left| \mathbf{c}^{\mathrm{H}} \mathbf{x}(t) \right|^2 \right\rangle \\
&= \mathbf{c}^{\mathrm{H}} \left\langle \mathbf{x}(t) \mathbf{x}(t)^{\mathrm{H}} \right\rangle \mathbf{c} \\
&= \mathbf{c}^{\mathrm{H}} R_{xx} \mathbf{c}
\end{aligned}
$$

where

$$
\mathbf{x}(t) = \begin{pmatrix} x_1(t) \\ x_2(t) \\ \mathrm{M} \end{pmatrix} \qquad \mathbf{c} = \begin{pmatrix} \exp(-\mathrm{i}kd_1 \sin\theta) \\ \exp(-\mathrm{i}kd_2 \sin\theta) \\ \mathrm{M} \end{pmatrix}
$$

$$
R_{xx} = \begin{pmatrix} \left\langle x_1(t) x_1(t)^* \right\rangle & \left\langle x_1(t) x_2(t)^* \right\rangle & \Lambda \\ \left\langle x_2(t) x_1(t)^* \right\rangle & \left\langle x_2(t) x_2(t)^* \right\rangle & \Lambda \\ \mathrm{M} & \mathrm{M} & \mathrm{O} \end{pmatrix}
$$

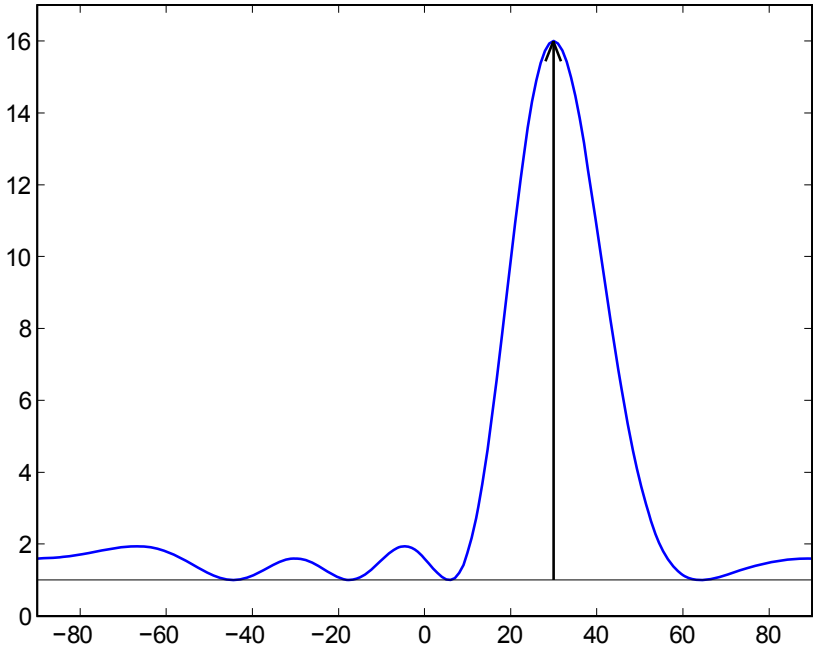
従来の位相マトリクスを用いたビーム形成法（Fourier法）



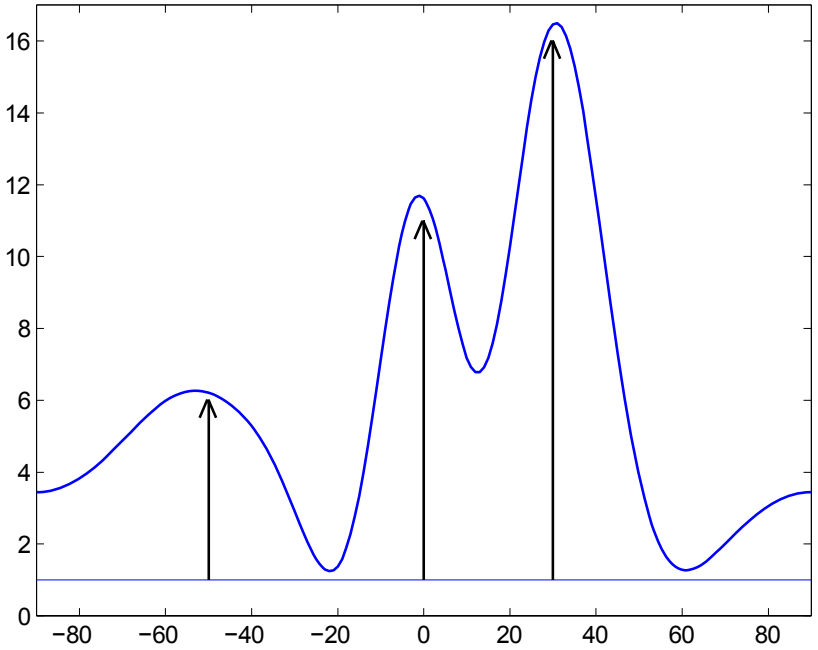
- 16組の固定の位相遅延量による位相マトリックスを用い、固定の16方向を切替え、HW内でアナログ的に合成した結果をPCに取込み。
（送信・受信とも）。
- ビーム幅は約3度で固定
- サイドローブの存在の為、望まない方向からの干渉波との区別が困難。

Images by Fourier Method

One target



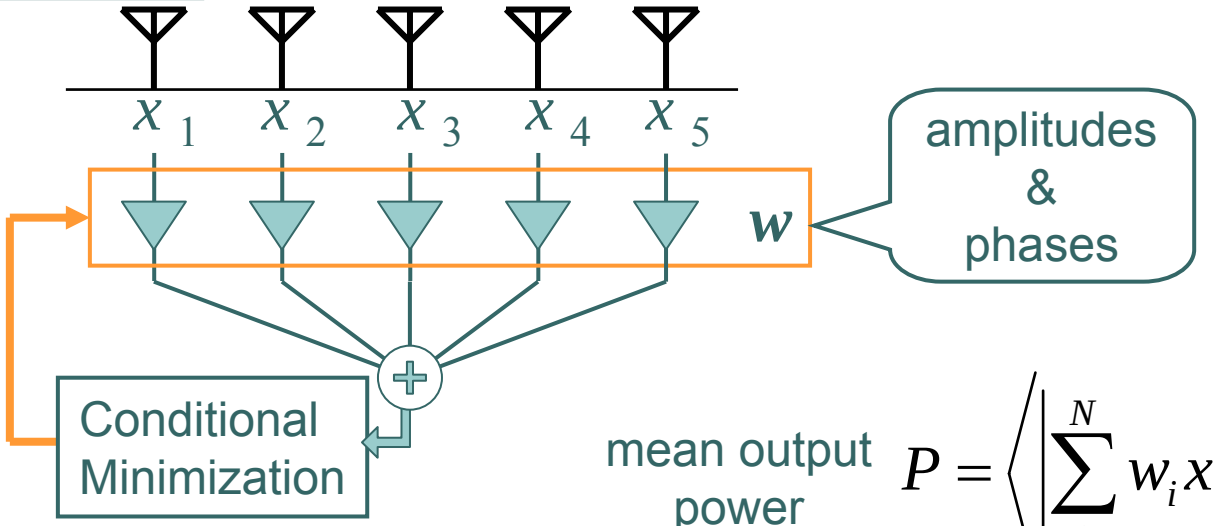
Three targets



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

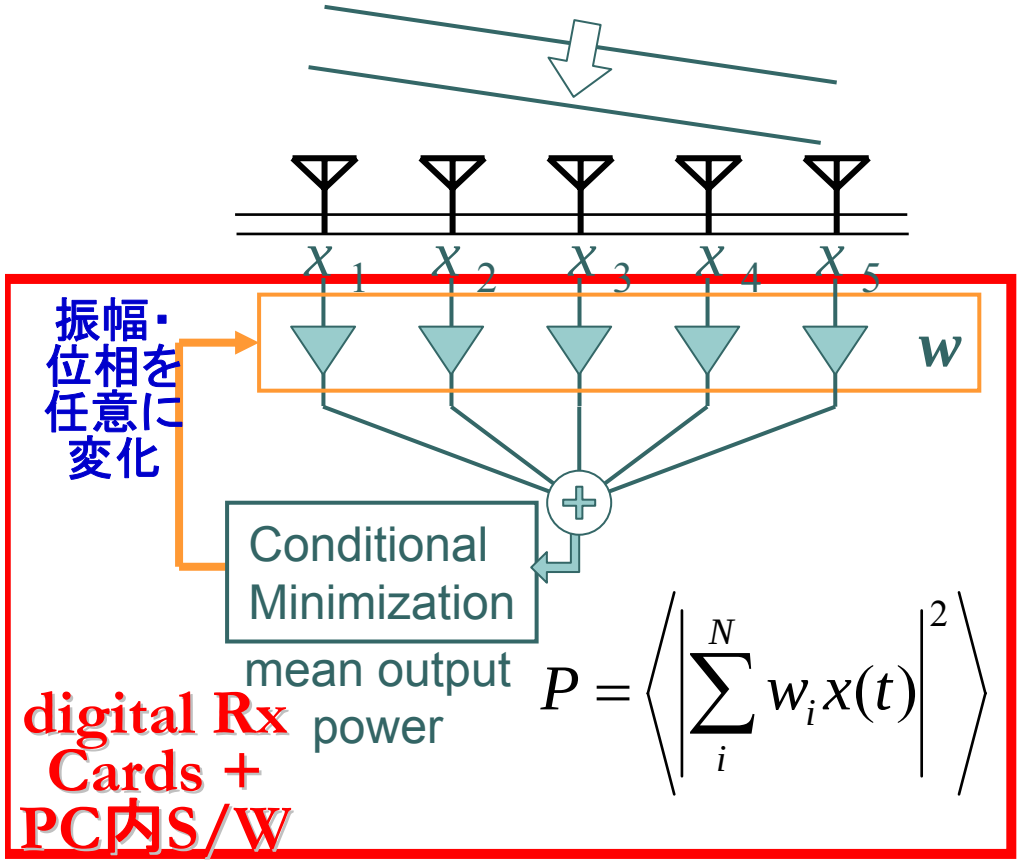
$$\underset{\mathbf{w}}{\text{minimize}} \left\{ P = \mathbf{w}^{\mathrm{H}} R_{xx} \mathbf{w} \right\}$$

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

Solution

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

Adaptiveなビーム形成法（Capon法）



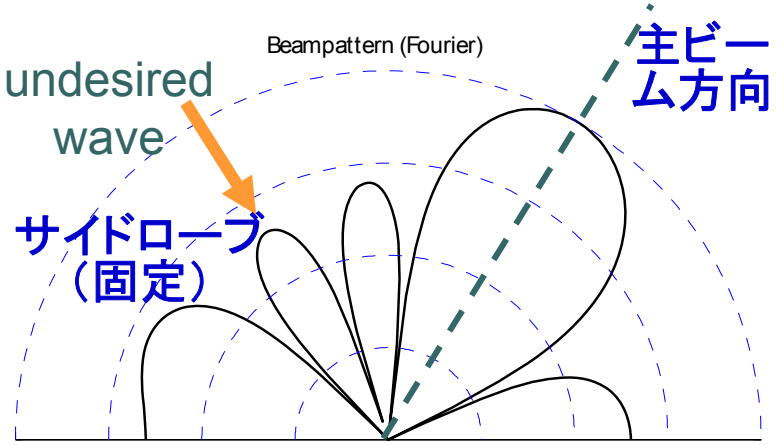
各アンテナ出力を別々にデジタル受信ボードで取込み、受信ビームもPC内S/Wで任意に形成。

- 受信時、各アンテナ出力を、位相matrixで合成することなく、個々に独立したデジタル受信ボードを介してPCに取込み、S/WでAdaptiveに（受信データに応じて）最適なビーム形成を行う。（送信は従来通り。）
- 主ビーム方向以外の不要な干渉波をAdaptiveに除去し、方位角方向に高い分解能を実現。
- 送信ビーム内のimagingも可能になる。（方位角分解能が飛躍的に増大）

（分解能はS/N比に寄るが、一桁上を狙う。）

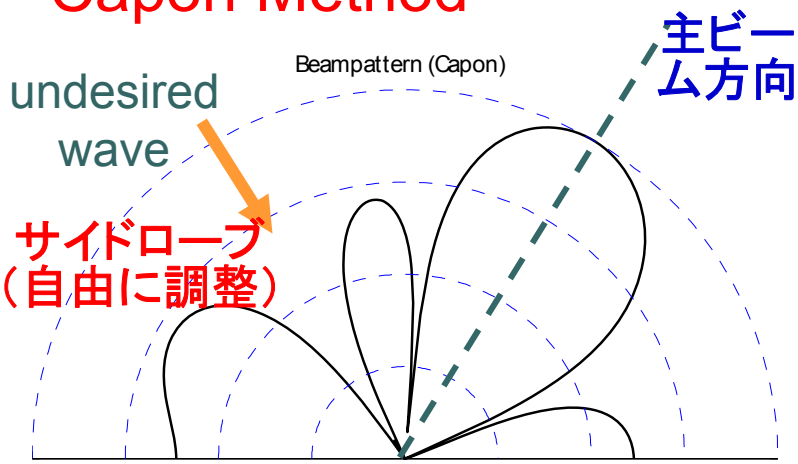
Fourier法とCapon法の比較

Fourier Method

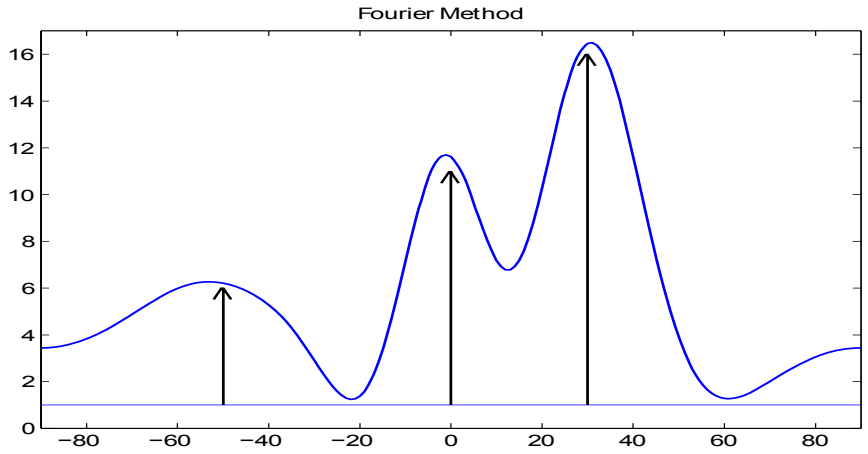


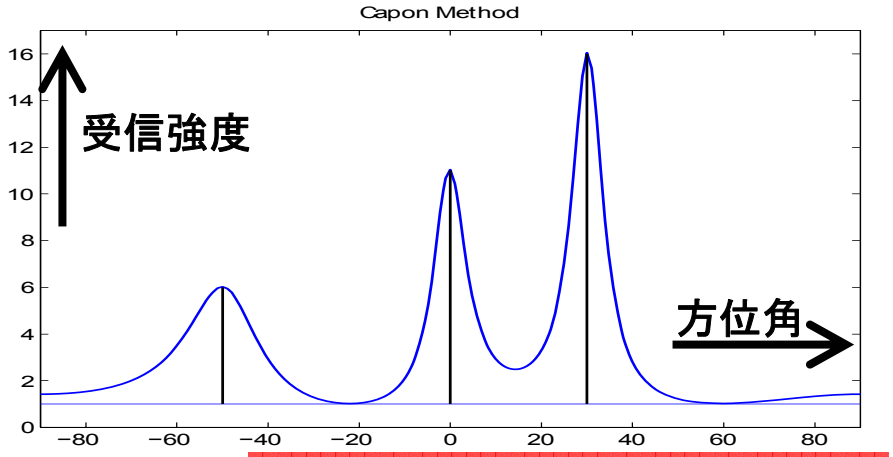
主ビーム以外の不要波を除去不能

Capon Method



主ビーム方向以外の不要波を除去。
ビーム内imagingを含む高い空間分解能実現。

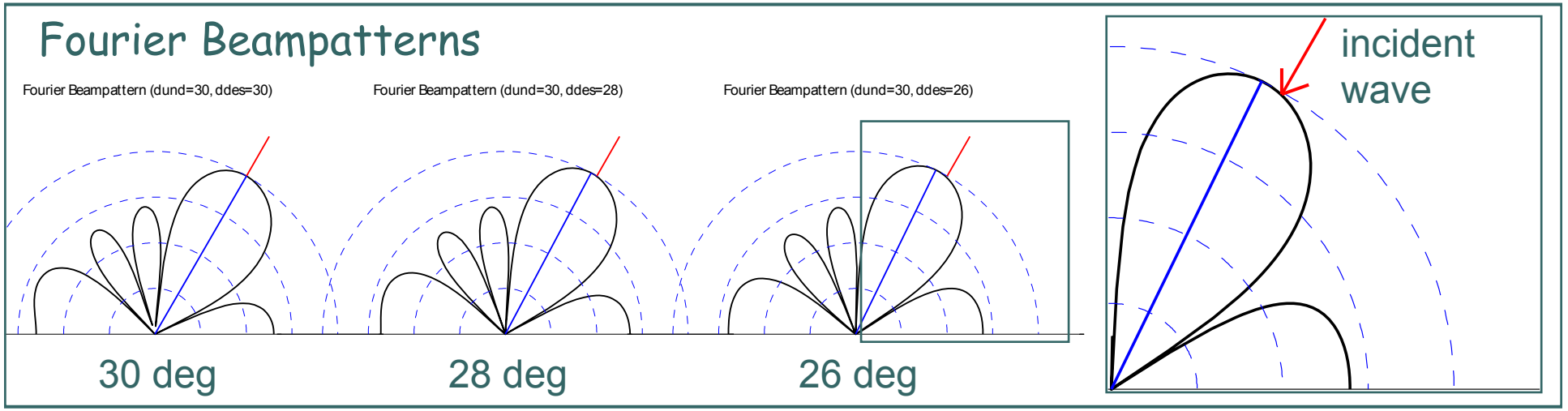


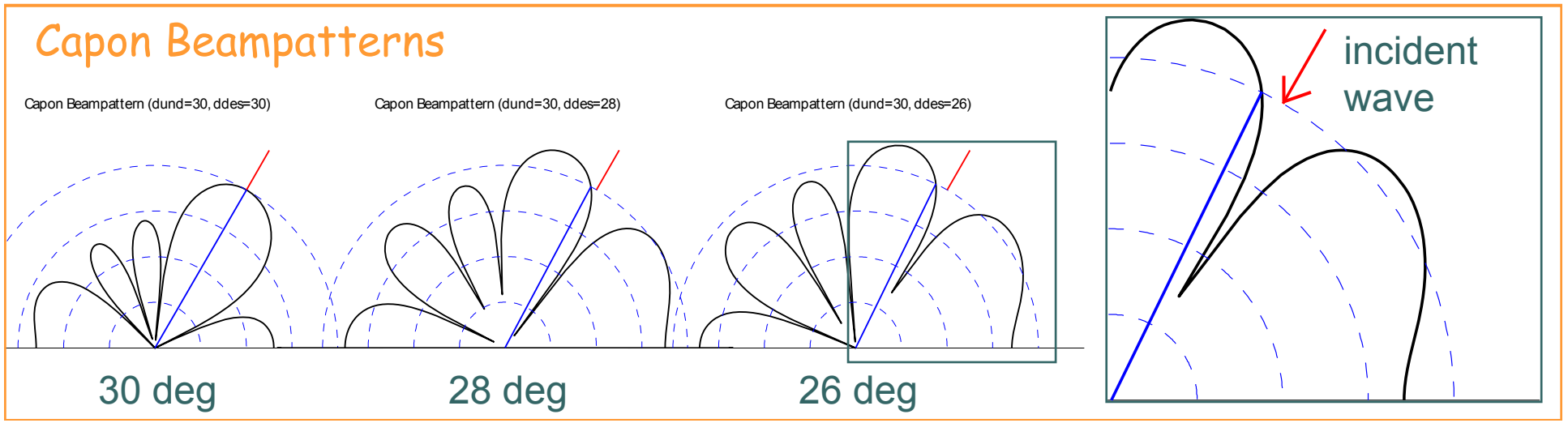


Resolution depends on S/N

Beampatterns by Fourier & Capon

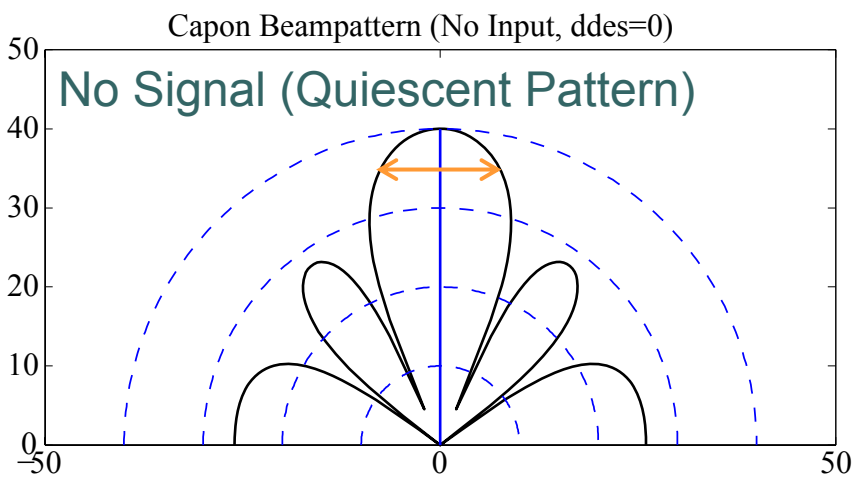
- Response around a strong signal (=30deg)

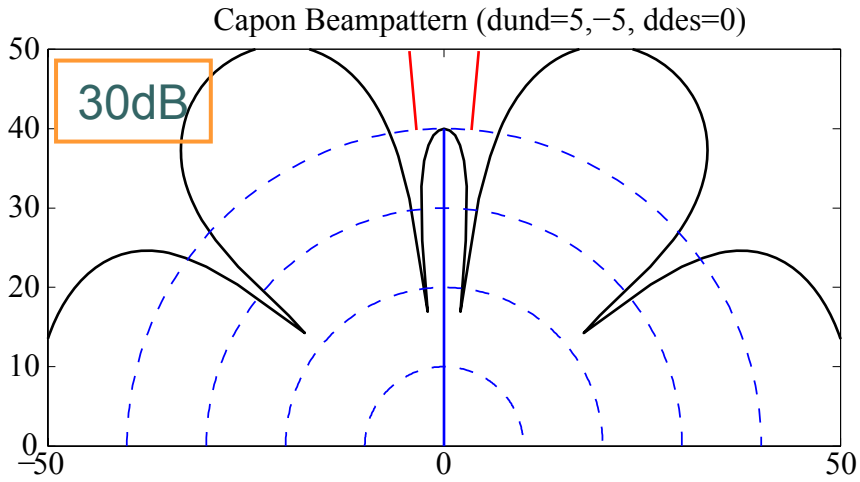


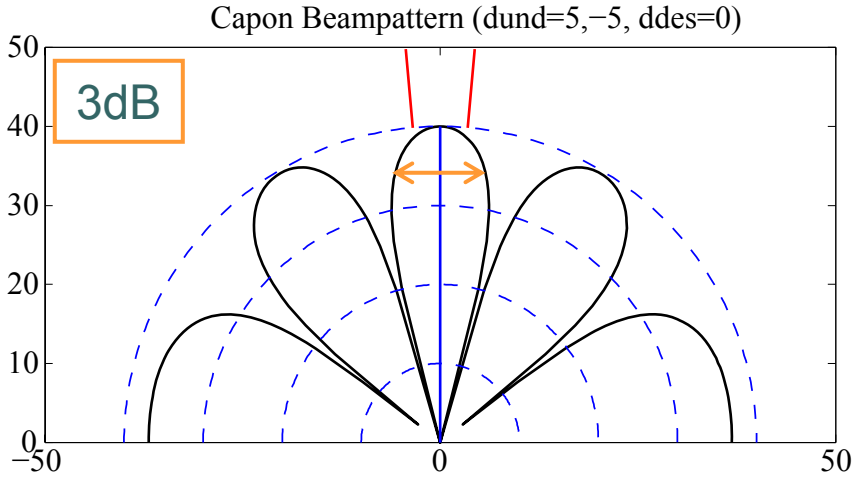


Capon Beampatterns

- Responses provides "High-Resolution"



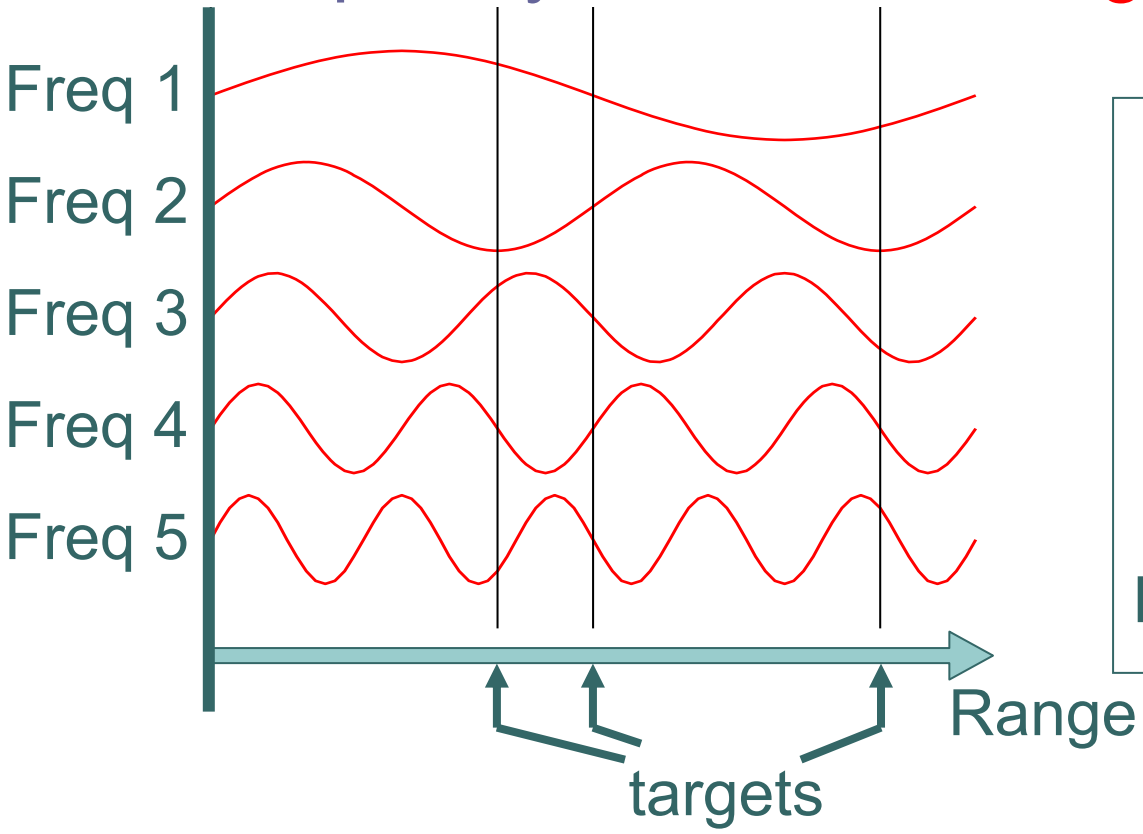




The optimizer creates a narrow main-lobe sacrificing the SNR (also sidelobes) when inputs are strong.

System in Frequency Domain: FDI

- Same principle can be applied to frequency domain for range imaging



Similarity

Range Space		Angular Space
Range	⟷	Angle
Multiple Freqs	⟷	Multiple Antenna
Frequency	⟷	Antenna Position

FDI range imaging

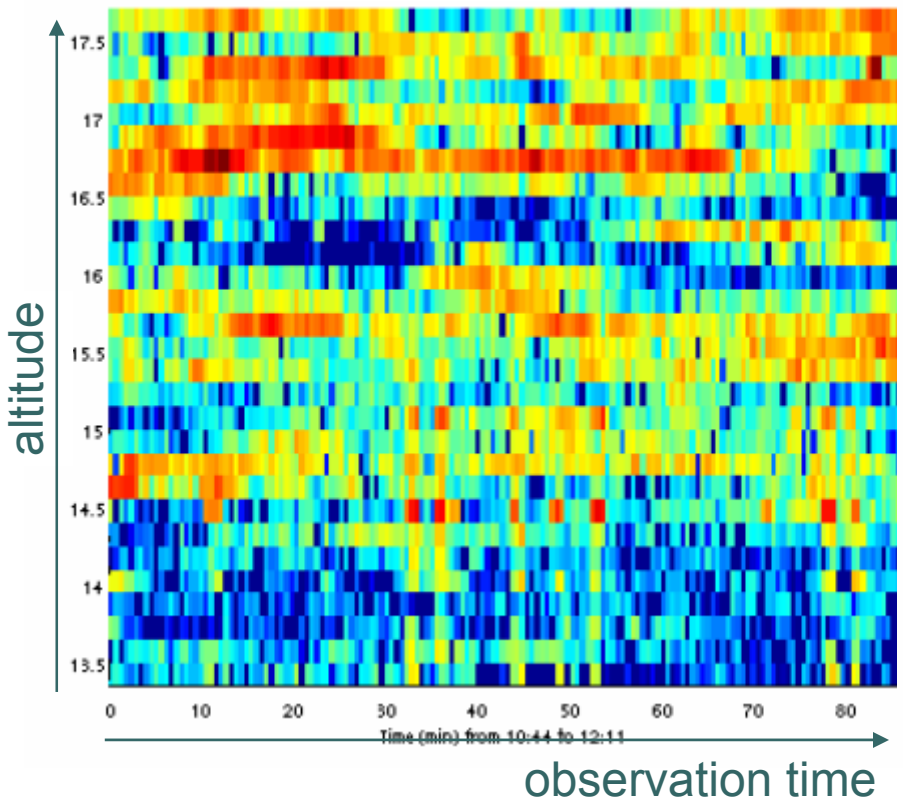
SDI angular imaging

FDI & SDI are mathematically equivalent!

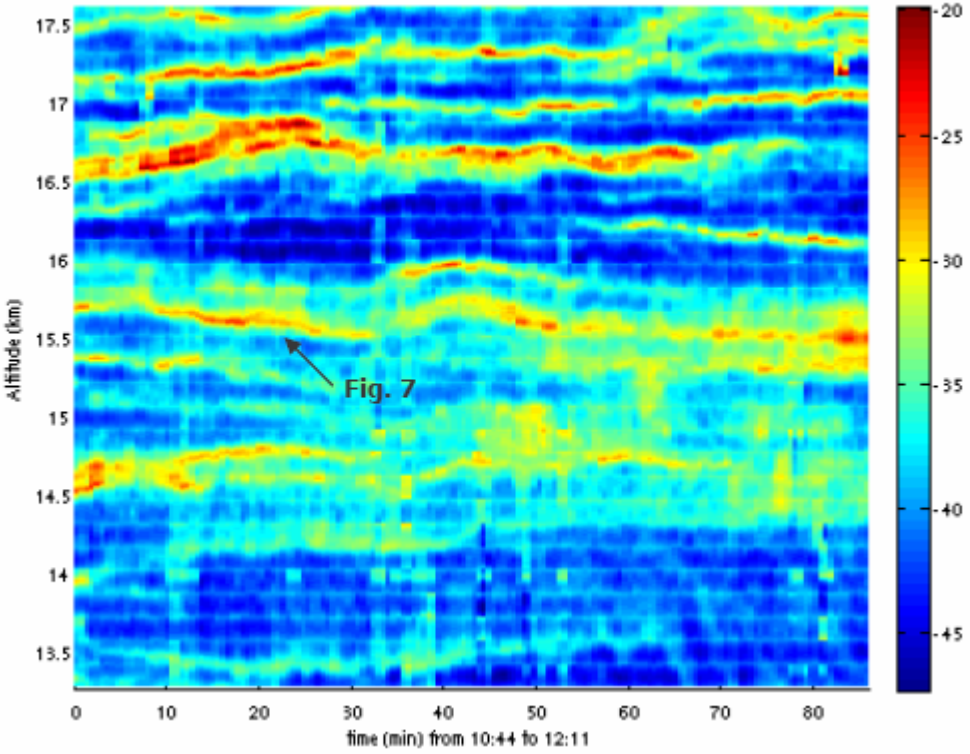
FDI in atmospheric radar

- 5 frequency observation with the MU Radar

Conventional



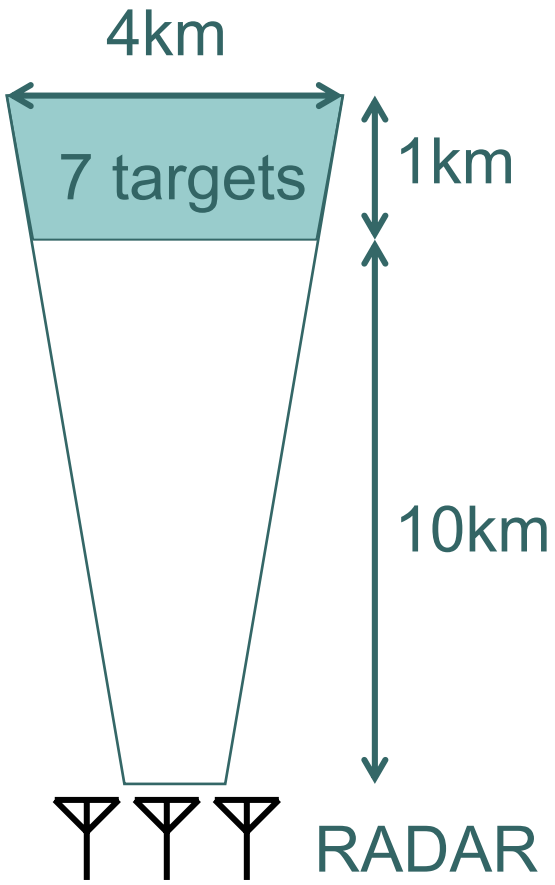
FDI



Luce, *Ann. Geophys.* 24, p.791, 2006.

Angular + Range High-Resolution

- 2D imaging simulation



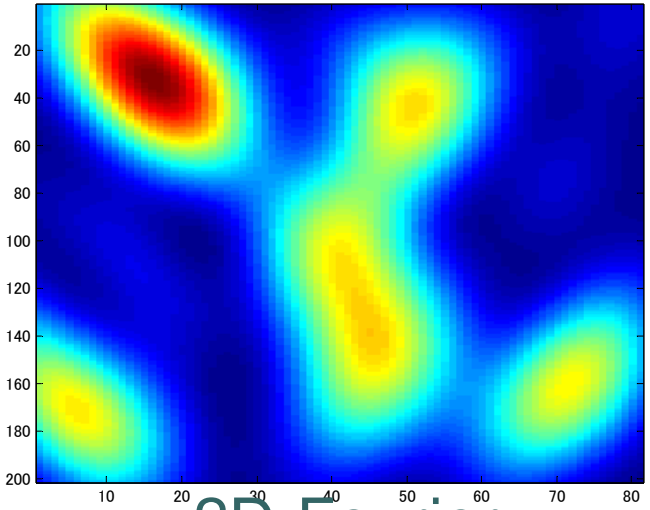
Radar

5 Antennas
Δx=3m (1λ)

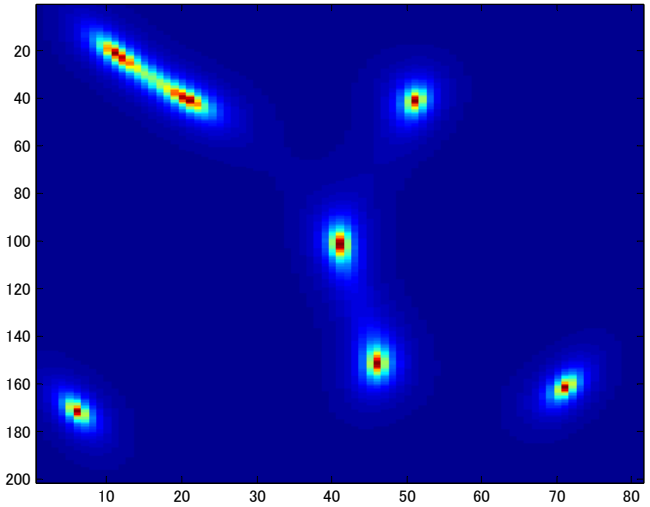
5 Frequencies
F_0=100MHz
ΔF=100kHz

Targets

7 targets
S/N=7dB each
infinite time observation



2D-Fourier



2D-Capon

Resolution of Capon/Fourier Imaging

An input signal for an equally spaced array with N elements is defined as

$$\sigma\mathbf{s} \text{ where } \mathbf{s} = [\exp(ikd\sin\theta), \Lambda, \exp(iNkd\sin\theta)]^T$$

The correlation matrix is then given by

$$R = I + \sigma^2 \mathbf{s}\mathbf{s}^H \text{ where } I \text{ is the unity matrix meaning noise.}$$

(Note that the statistical fluctuation is ignored.)

Now we define the steering vector

$$\mathbf{c} = [\exp(ikd\sin\theta), \Lambda, \exp(iNkd\sin\theta)]^T / \sqrt{N}$$

This is normalized so that $\|\mathbf{c}\|^2 = 1$

Then the beampattern (complex) is derived

$$f(\theta) = \frac{\mathbf{s}^H \mathbf{c}}{\sqrt{N}} \quad \text{note that} \quad 0 \le |f(\theta)|^2 \le 1$$

Resolution of Capon/Fourier Imaging

Fourier Imaging (non-adaptive)

The image by the Fourier method for a single point source is

$$P_F(\theta) = \mathbf{c}^H \mathbf{R} \mathbf{c}$$

$$= \mathbf{c}^H [I + \sigma^2 \mathbf{s}\mathbf{s}^H] \mathbf{c}$$

$$= 1 + \sigma^2 N \left| f(\theta) \right|^2$$

$$= 1 + \sigma^2 N P_F'(\theta)$$

Note that "1" means the normalized noise level and the sigma^2 corresponds to the signal-to-noise ratio.

The 3dB resolution is defined by θ_F^{3dB} where the 2nd term gives

$$P_F'(\theta_F^{3dB}) = \left| f(\theta_F^{3dB}) \right|^2 = \frac{1}{2}$$

Resolution of Capon/Fourier Imaging

Capon Imaging (adaptive)

The image by the Capon method for the same condition is

$$P_C(\theta) = \frac{1}{\mathbf{c}^H R^{-1} \mathbf{c}} = \frac{1}{\mathbf{c}^H [I - \frac{\sigma^2 \mathbf{s}\mathbf{s}^H}{1+N\sigma^2}]\mathbf{c}} = \frac{1}{1 - \frac{\sigma^2 N}{1+N\sigma^2}|f(\theta)|^2}$$

$$= 1 + \frac{\sigma^2 N |f(\theta)|^2}{1+\sigma^2 N (1-|f(\theta)|^2)} = 1 + \sigma^2 N P'_C(\theta)$$

The 3dB resolution is derived by the equation $P'_C(\theta_C^{3dB}) = \frac{1}{2}$ which gives the relation

$$|f(\theta_C^{3dB})|^2 = \frac{1}{2}\left(\frac{1+\sigma^2 N}{1+\sigma^2 N/2}\right)$$

Resolution of Capon/Fourier Imaging

Comparison between Fourier & Capon resolutions

It is difficult to describe θ_C^{3dB} and θ_F^{3dB} directly, so compare the properties of $\left|f(\theta_C^{3dB})\right|^2$ and $\left|f(\theta_F^{3dB})\right|^2$.

$$\frac{1-\left|f(\theta_F^{3dB})\right|^2}{1-\left|f(\theta_C^{3dB})\right|^2} = 1+\frac{\sigma^2 N}{2} \approx \frac{\sigma^2 N}{2} \quad \text{where } \sigma^2 N >> 1$$

Since a beampattern is well approximated by the parabolic function around the main-lobe, the effect narrows the resolution by the factor of

$$\frac{\text{Resolution of Capon}}{\text{Resolution of Fourier}} \approx 1\Big/\sqrt{1+\frac{\sigma^2 N}{2}} \approx 1\Big/\left(\sigma\sqrt{\frac{N}{2}}\right)$$

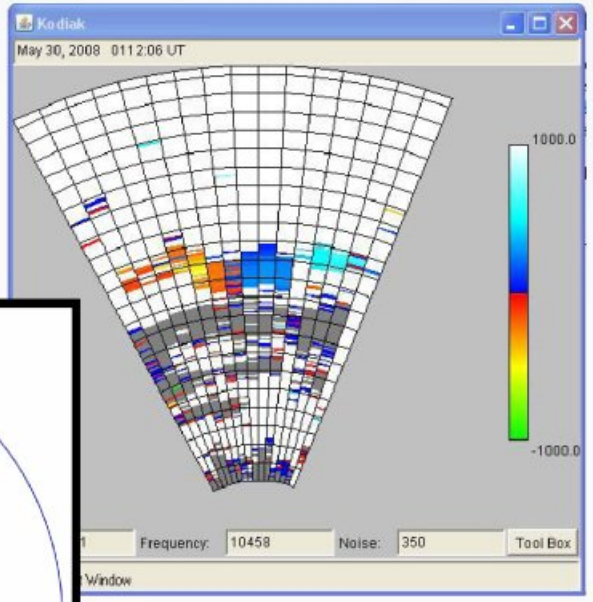
Direct Digital Synthesis Up-Converters

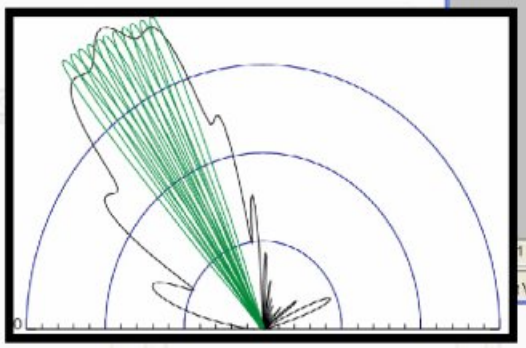
- Four ICS-660B DDS Cards
  - Four digital-to-analog converters
  - Four GC4116 digital up-converter chips per card
    - Four independent up converter channels per chip, one chip per DAC
    - 64 total DDS channels, four per Tx antenna
    - Permits ‘super stereo’ Tx
  - Full TX waveform control
- Drivers written under QNX Neutrino 6.3
  - TCP message passing to communicate with ROS
- In operation since September 2007

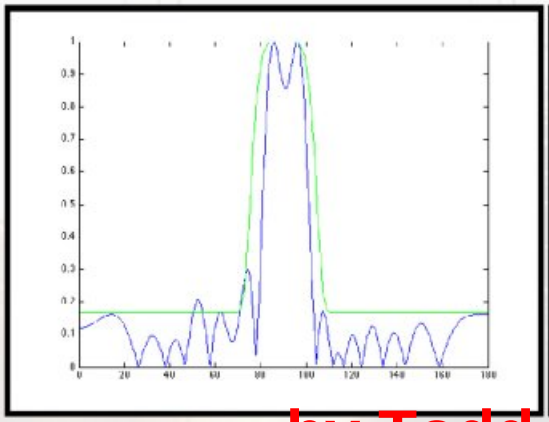
by Todd Parris @ SD2008

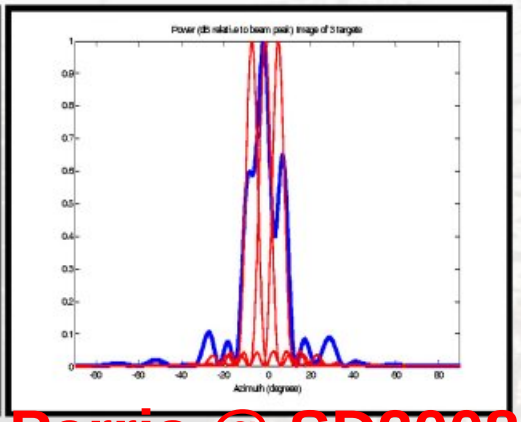
Some benefits of DDS on each antenna

- Phase coding
  - Binary, Quadrature, etc.
  - Phase coding modes have already been run for extended times
- Adaptive beam forming
  - Work in progress
  - Shown to work in lab
  - S. Shuxiang currently working on implementing adaptive beam forming on the Kodiak radar
  - Adapt Tx beam to ionospheric and noise condition to maximize observations (both temporally and spatially)
  - Image within TX beam for high spatial resolution measurements





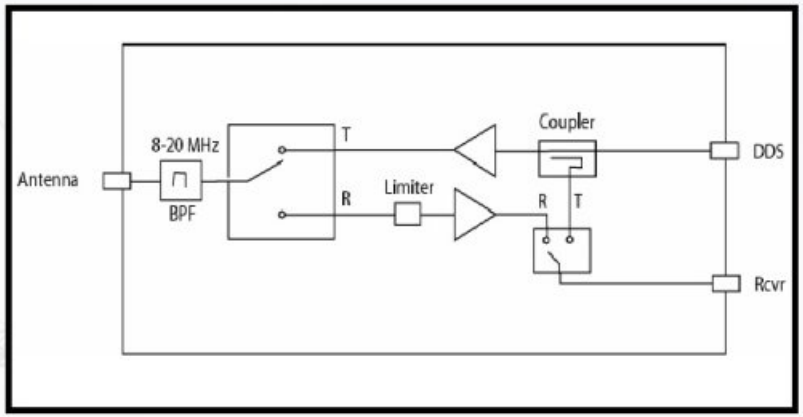


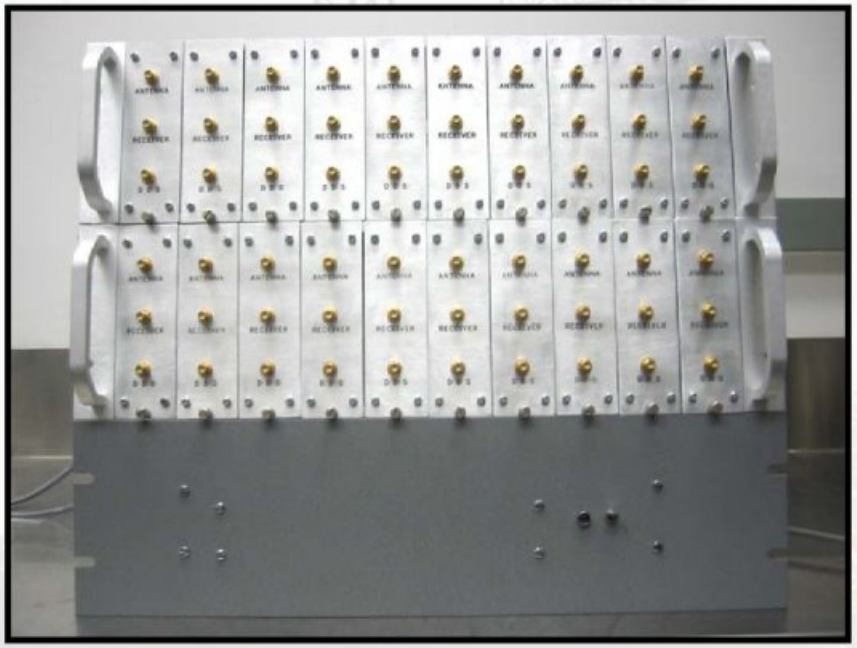


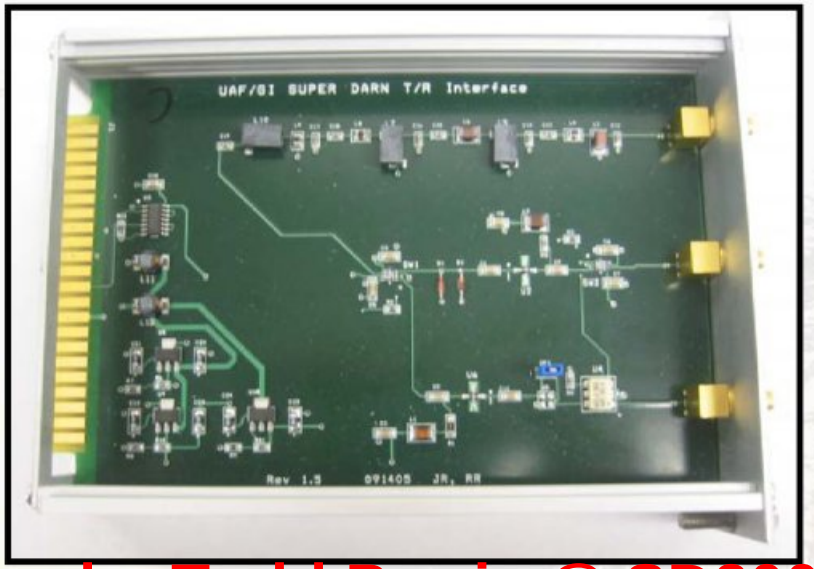
by Todd Parris @ SD2008

DDS/Digital Receiver interface hardware

- New hardware interfaces the receivers and DDS up-converters with amps, filters, and antennas
- Couplers allow direct sampling and characterization of the TX signal







by Todd Parris @ SD2008

Digital Imaging Receivers

- For our implementation, we have chosen the Echotek GC314-PCI/FS
  - 3 analog inputs and A/Ds
  - 100 MHz sampling
  - 4 receiver channels per antenna
    - Allows 'super stereo'
  - Up to 2 MHz BW per channel
  - 7 GC314s total
- 1021 sample FIFOs on each channel
  - Can only move 12 MB/sec off of these cards over PCI bus, which limits our achievable continuous sample rate
    - Less than 150 kS/s for single channel
    - Less than 75 kS/s for double channel
    - Less than 38 kS/s for quad channel
  - Can collect up to 1021 samples at any rate up to 2 MS/s
  - Still uses old GC214-PCI/TS with phasing matrix for some experiments
  - Currently using GC214 and phasing matrix for clear frequency search
- Sample DDS signals directly (via coupler)

by Todd Parris @ SD2008

Digital Imaging

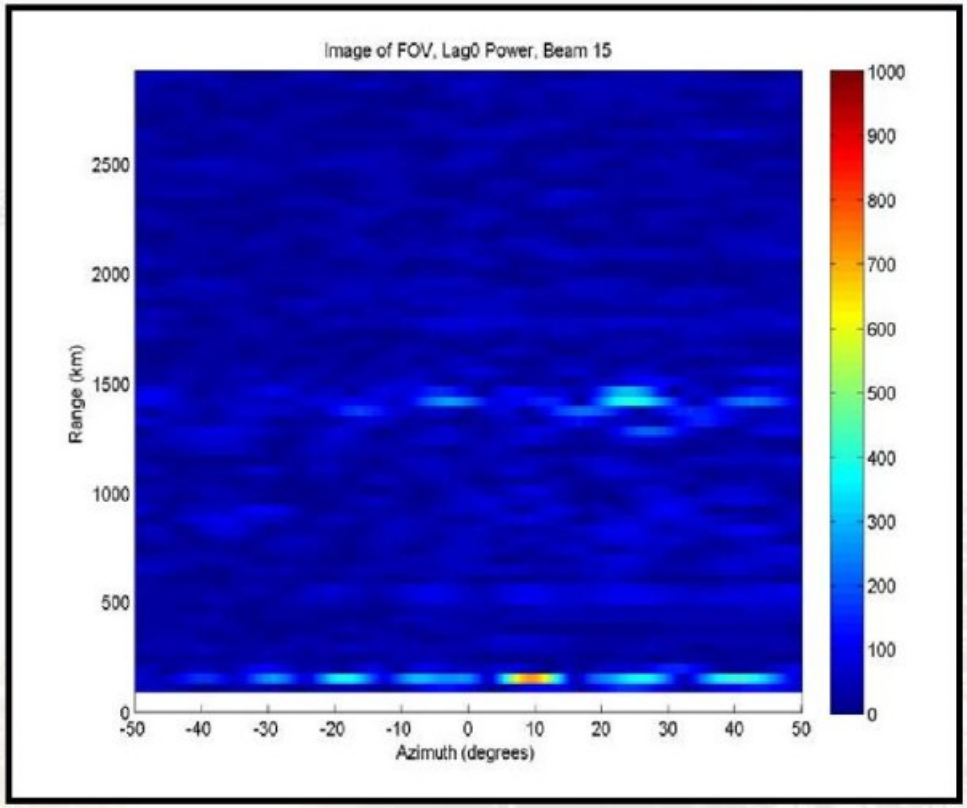
- Sample all antennas simultaneously
- Take FFT across array to get Bartlett estimation of brightness distribution

$$S_k(t) = \sum_{n=0}^{15} s_n(t) e^{-\frac{2\pi}{N} ink} \qquad k=0,\ldots,N-1$$

This is the digital analog of Using phasing matrix for many Directions at the same time

- Use some other spectral estimation to get higher resolution brightness distribution
  - Yule-Walker
  - Modified Co-variance
  - MUSIC
  - Many others….

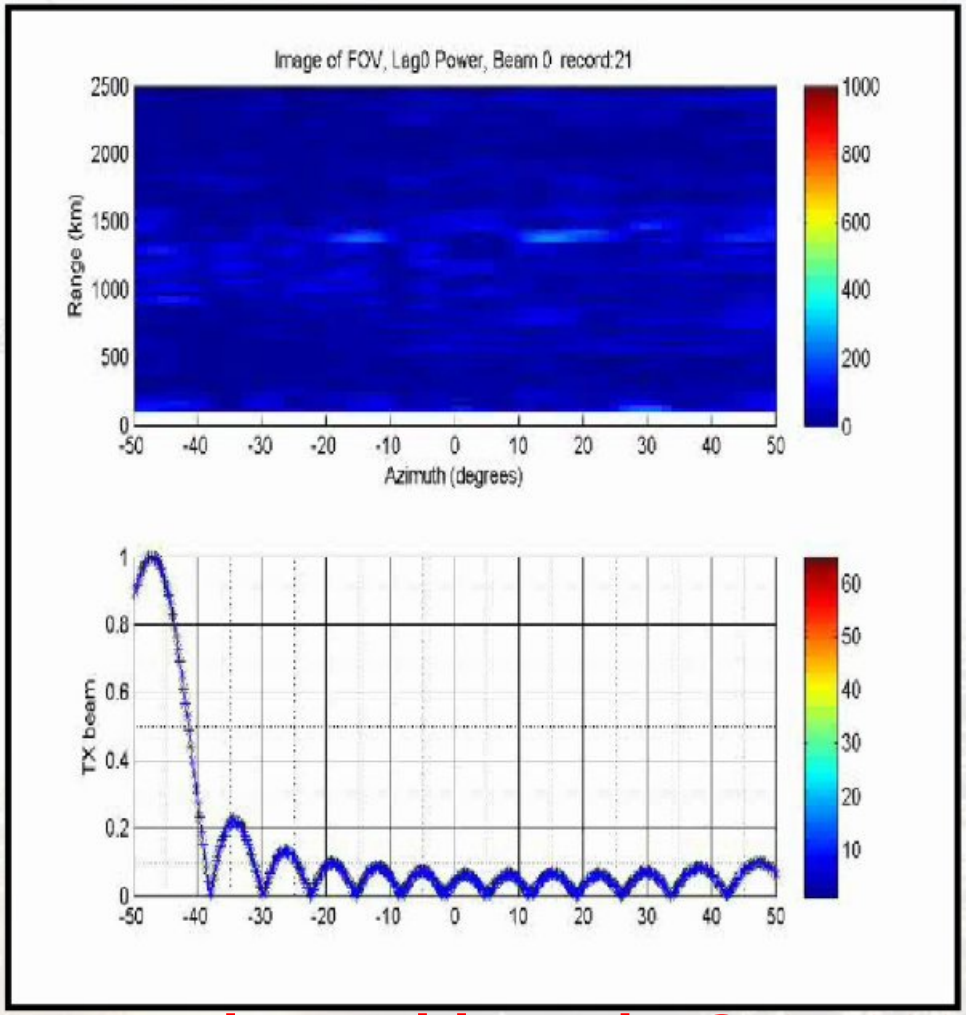
One of the first image from Kodiak



by Todd Parris @ SD2008

First Images

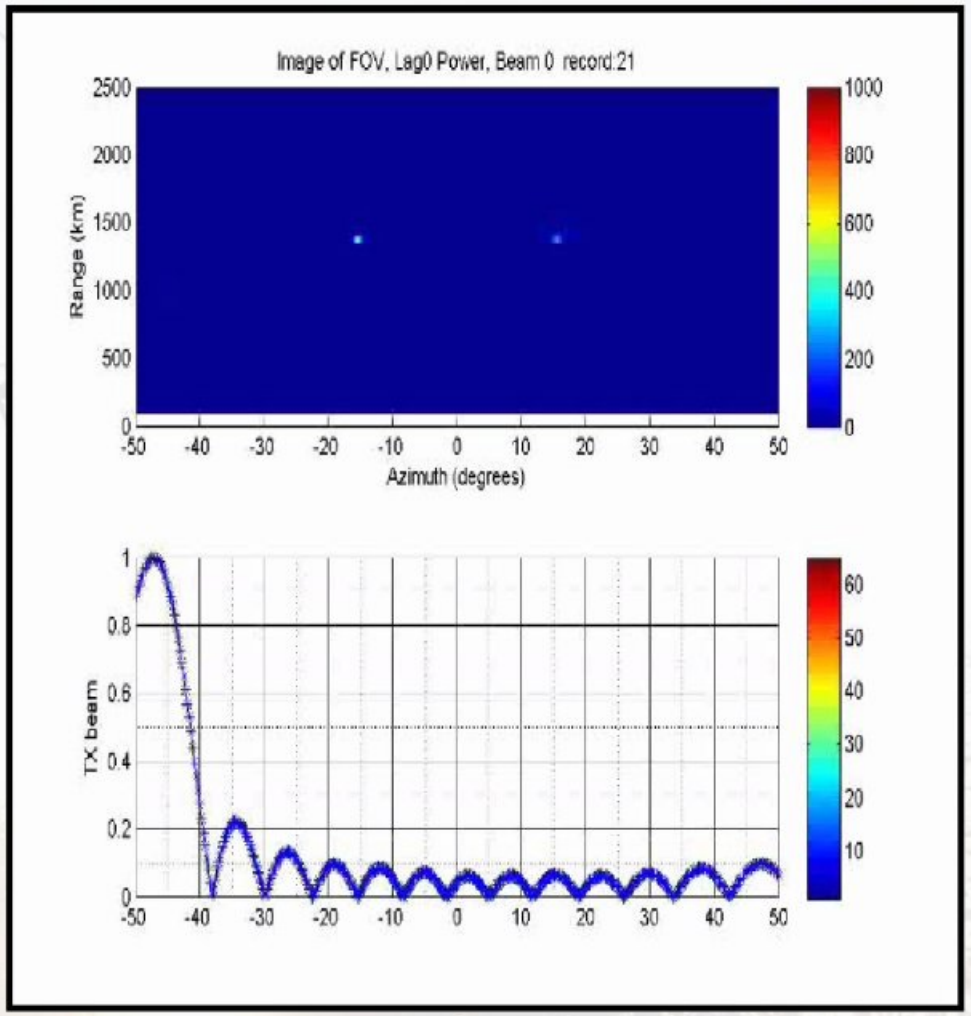
- These are very preliminary results
- Imaging receivers just installed last week
- Radar parameters for images shown here;
  - Normalsound-fast
  - 10.4-10.7 MHz band
- TX beam shown is signals provided to transmitter
  - Actual TX signal depends on state of transmitters
  - Data shown was collected after all transmitters were fixed and calibrated



by Todd Parris @ SD2008

Higher resolutions

- Other brightness distribution estimators can be used to increase azimuthal resolution
- Modified covariance estimator is shown
- Others;
  - Yule-Walker
  - MUSIC
  - De-convolutions
  - Etc.
- Achievable resolution is determined by SNR, not antennas



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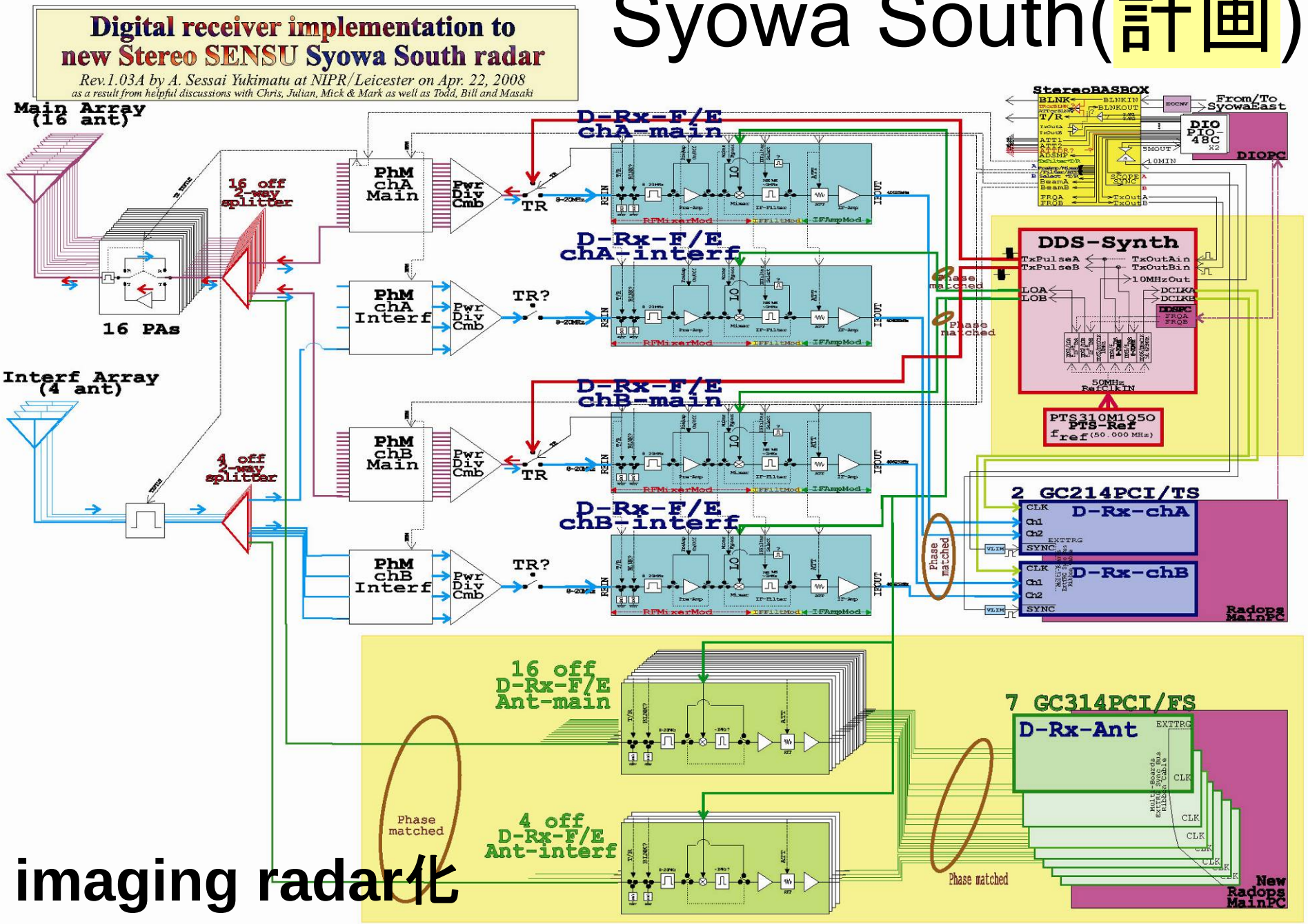
Syowa South(計画)

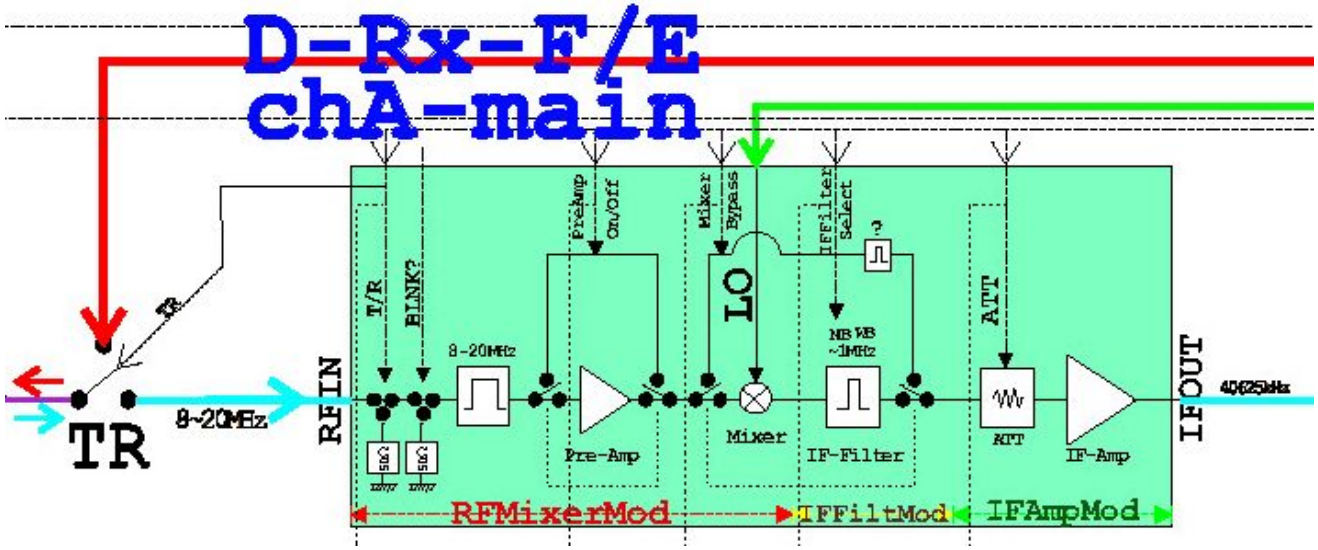


imaging radar化

IF/RF sampling

- There exist 2 ways of digital Rx usage:

1) IF sampling : w/ mixer+LOin and IF filter in DRFE
   a DigiRx card samples an IF (only 1 TxFreq)
   high selectivity : tough under noisy radio env.
2) RF sampling : w/o mixer in DRFE - simple
   a DigiRx card samples RF (up to 4 TxFreq)
   all 8-20M band goes to digiRx
   noisy radio env. might cause problems



短波レーダーの一部更新と保守

- デジタル受信機系への移行はほぼ完了（HF1,49次）
  - RF samplingとIF samplingの比較
  - imaging radar化(方位角方向)計画

（位相マトリクスを介さず各アンテナ受信出力を取得し、adaptiveな受信ビーム生成可能な受信システム系への更新。RF sampling問題なければステレオ化も容易。昭和持込前に北欧で動作確認。）

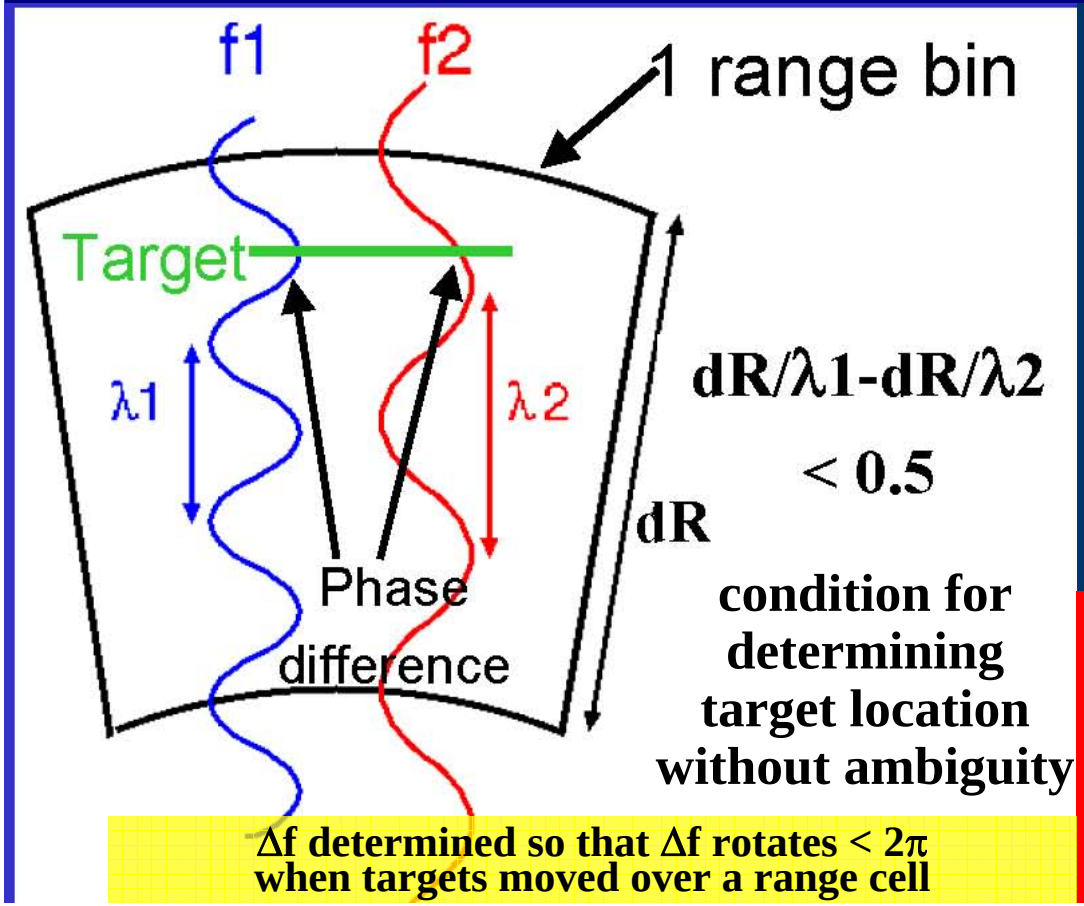
  - 送信ビーム生成のデジタル化
  - 2レーダーの送信タイミングの制御

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** (**Δ f~kHz**)
Infer **fine range location within a range cell**
using **phase differences** by **dual freq observation**



dR/λ1-dR/λ2
< 0.5

condition for determining target location without ambiguity

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

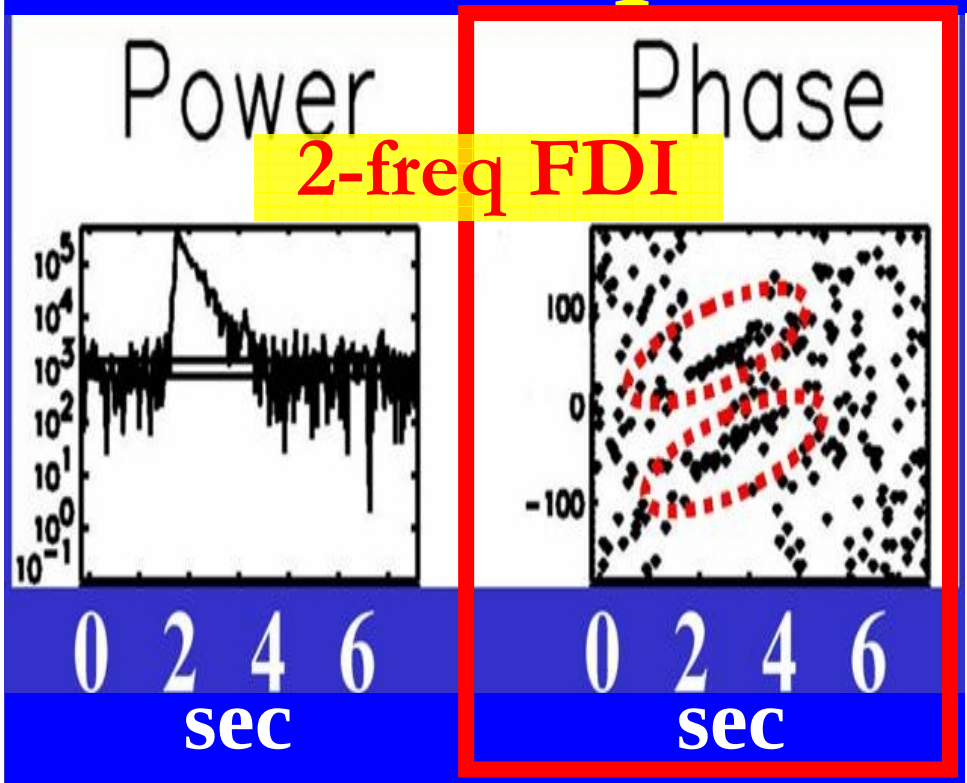
freq difference

|Δ f | < dR/c

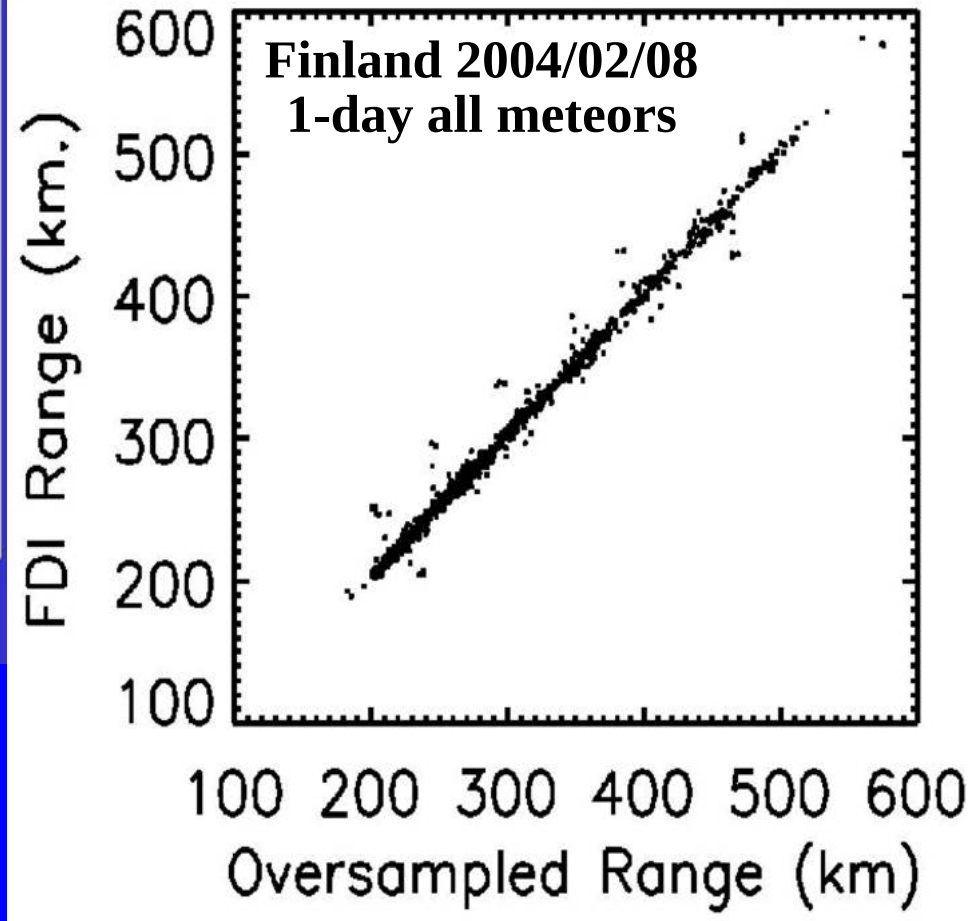
|Δ f | < 3.33 kHz (rsep 45km)
|Δ f | < 5.0 kHz (rsep 30km)
|Δ f | < 10 kHz (rsep 15km)

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

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



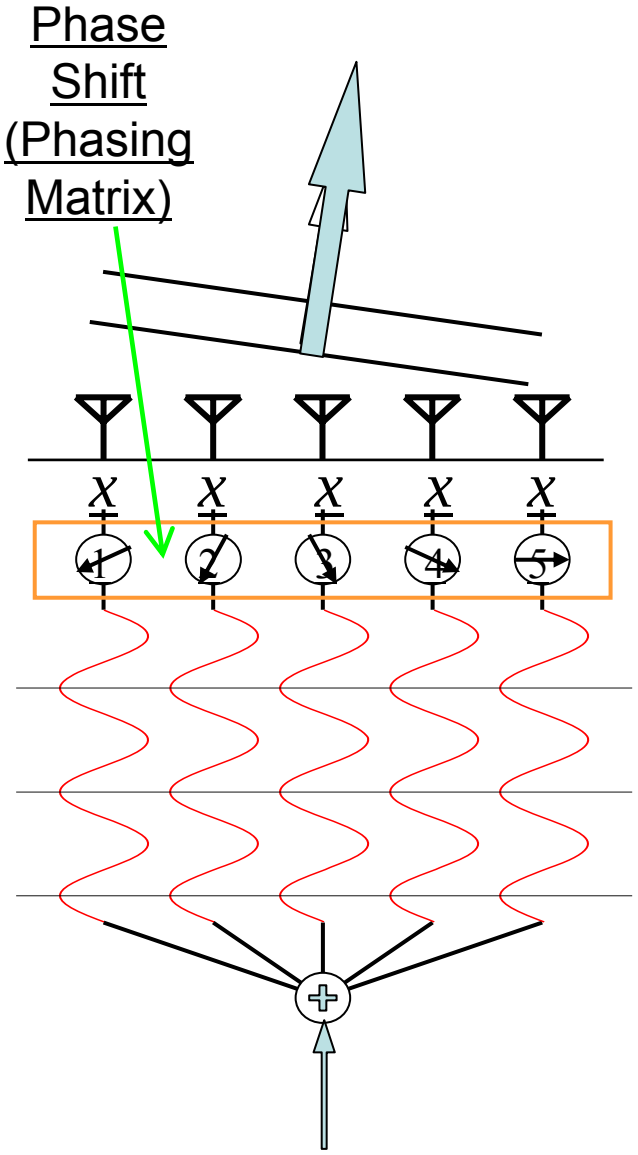
Change TxFreq every pulse sequence (i.e., Tilt TxFreq), 2 phase groups seen



FDI vs Over-Sampling
Nice Agreement!

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.

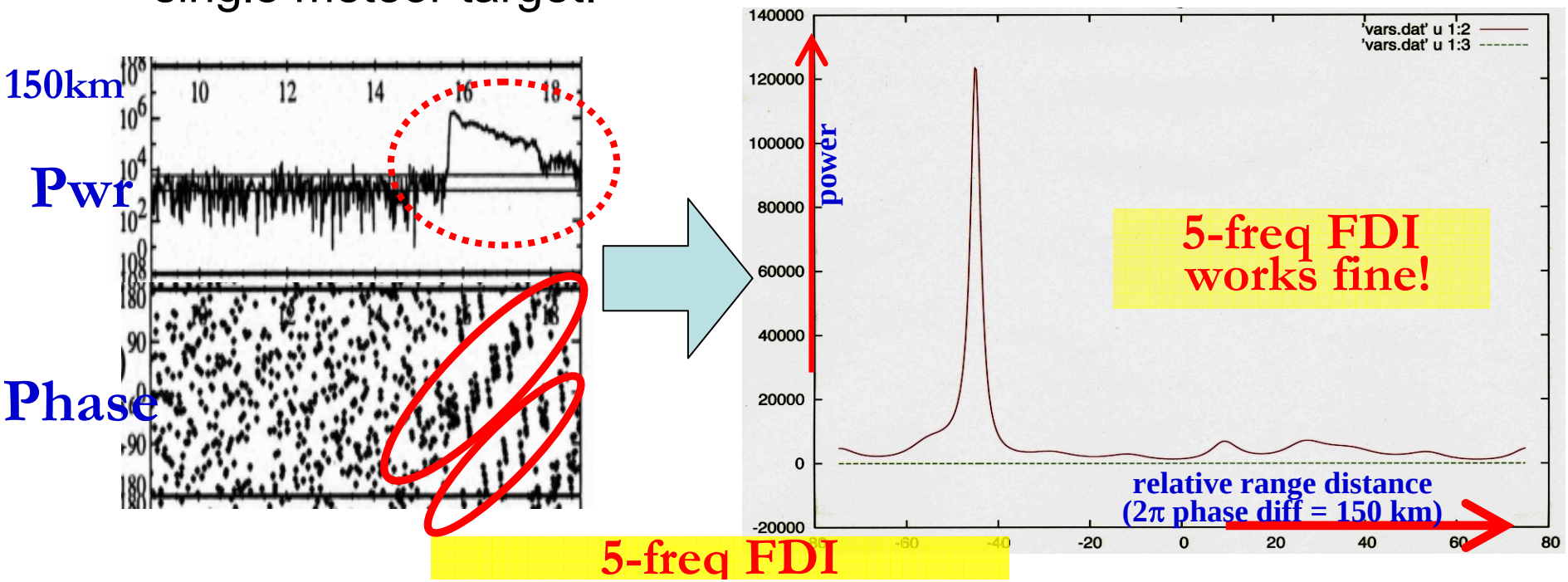


FDI "initial phase" determination

- 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...

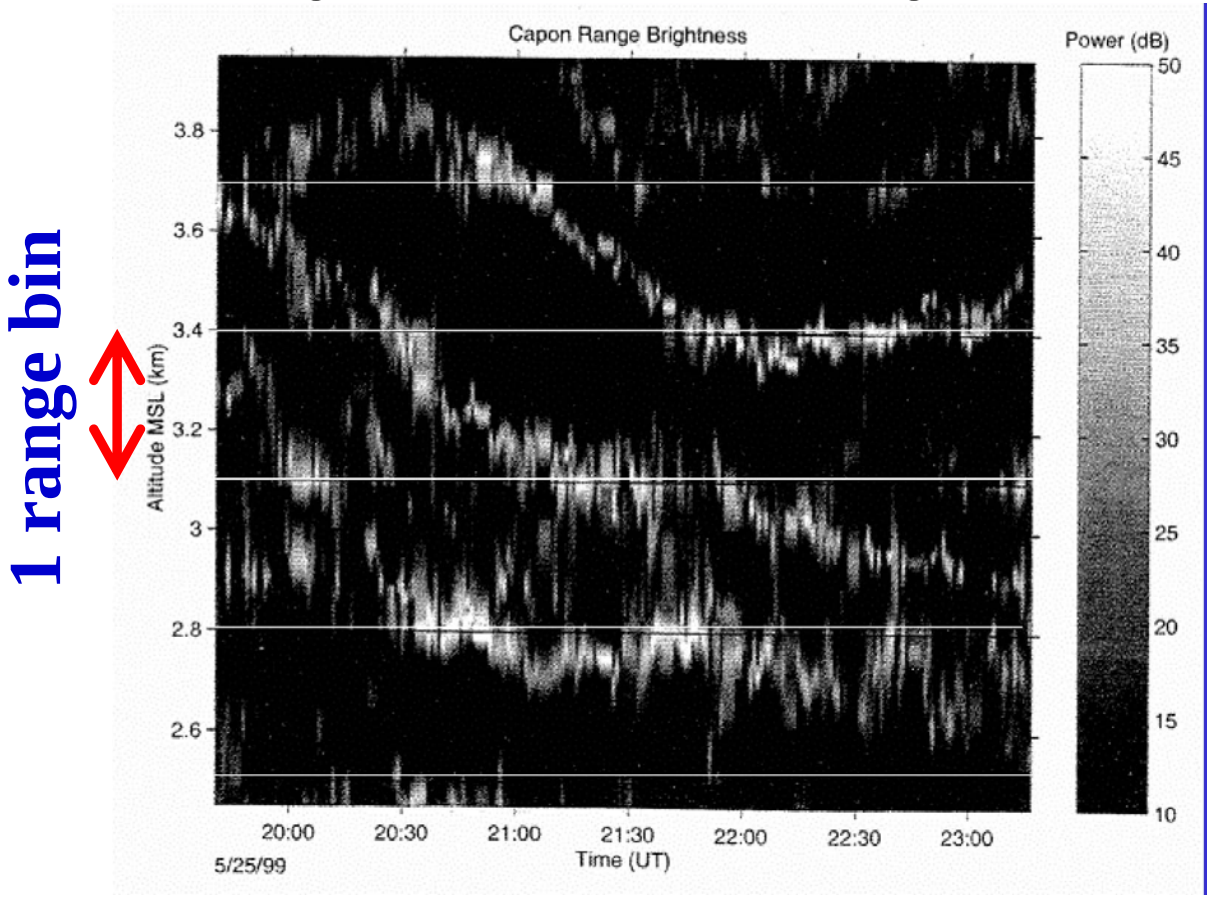
FDI "initial phase" determination

- 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

- 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

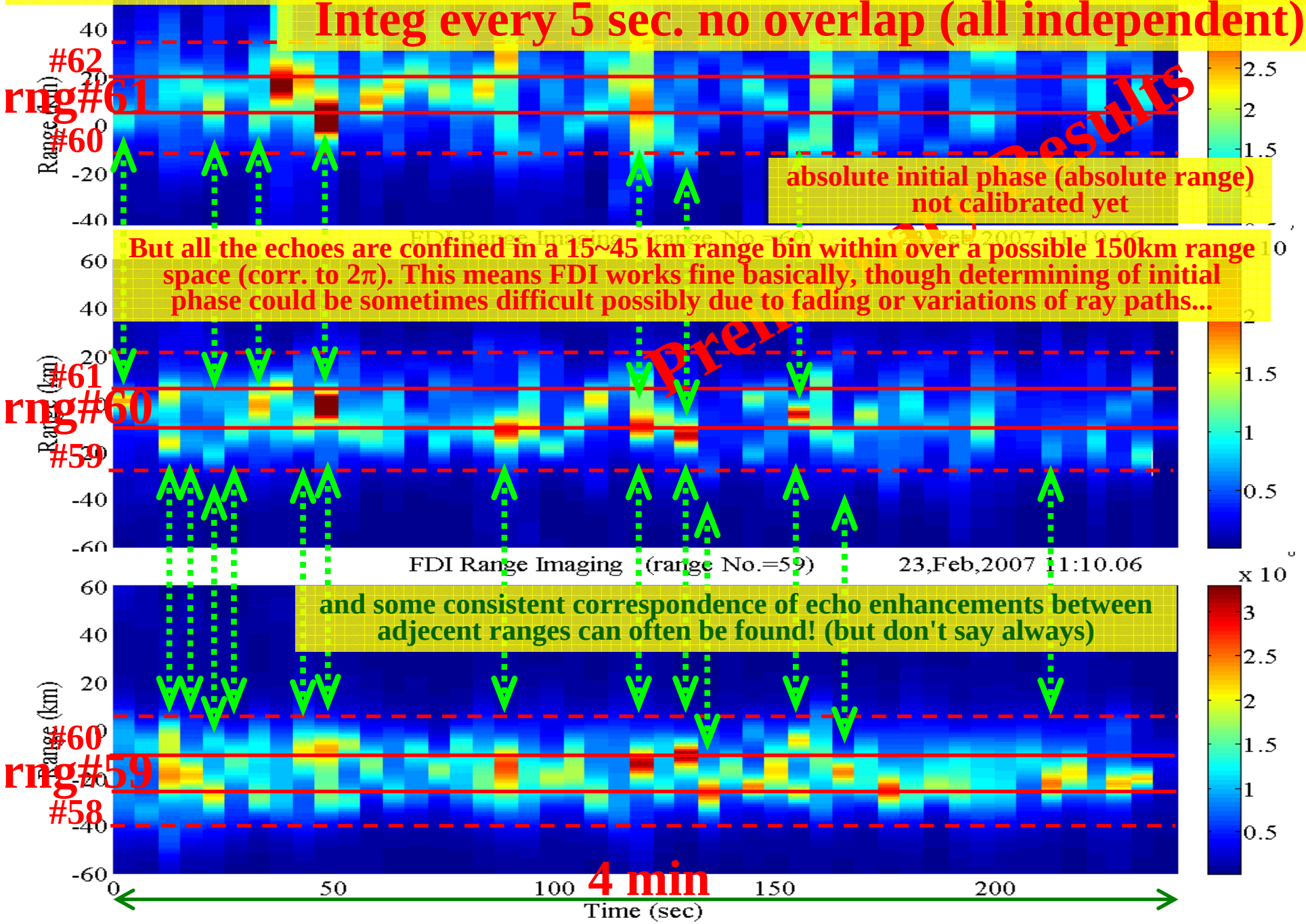
FDI resolved much thinner turbalence layer structures within range cells

FDI "initial phase" determination

- 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...

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

Integ every 5 sec. no overlap (all independent)



FDI results (for a worse case)

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

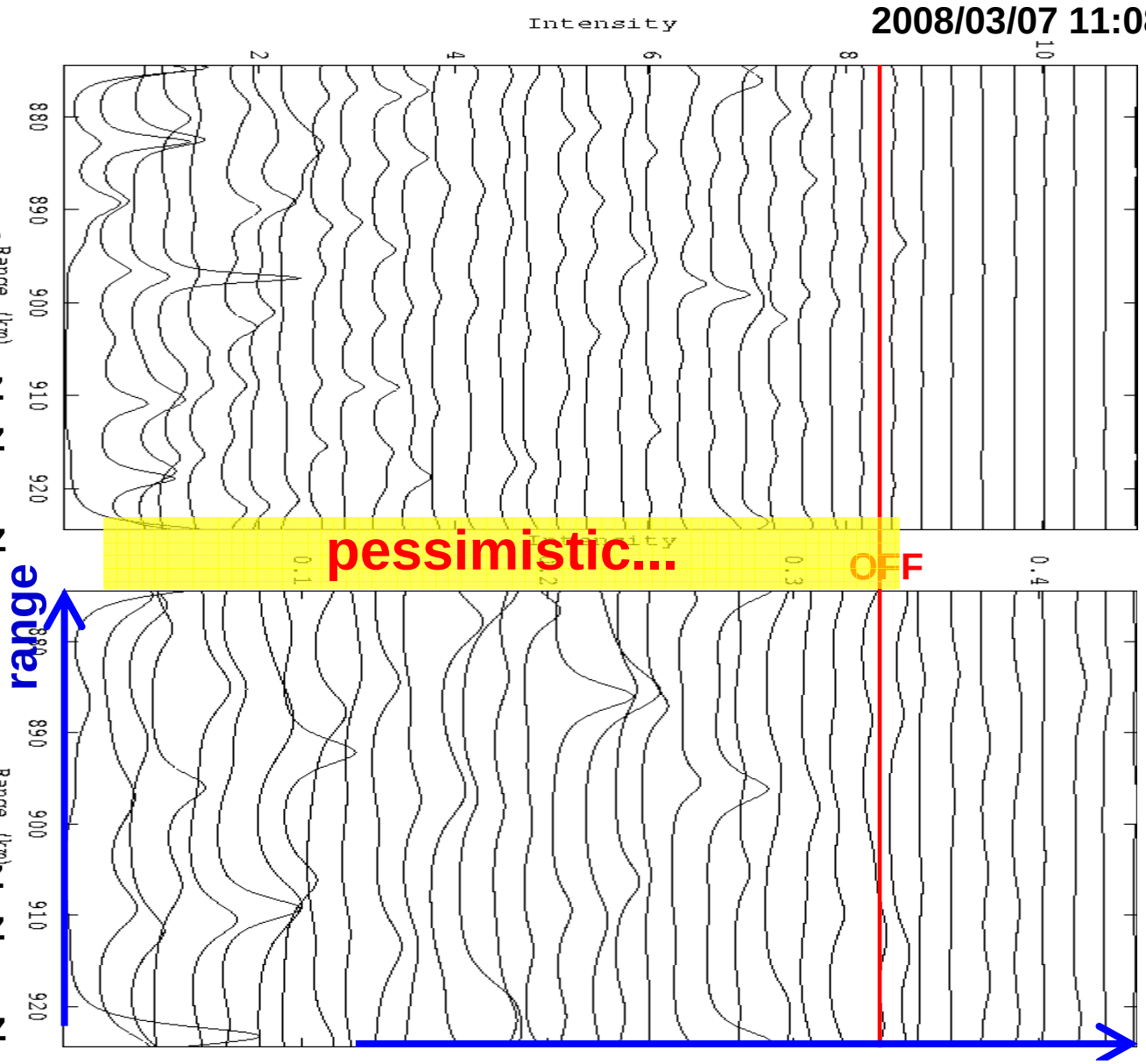
2008/03/07 11:08-11:09

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

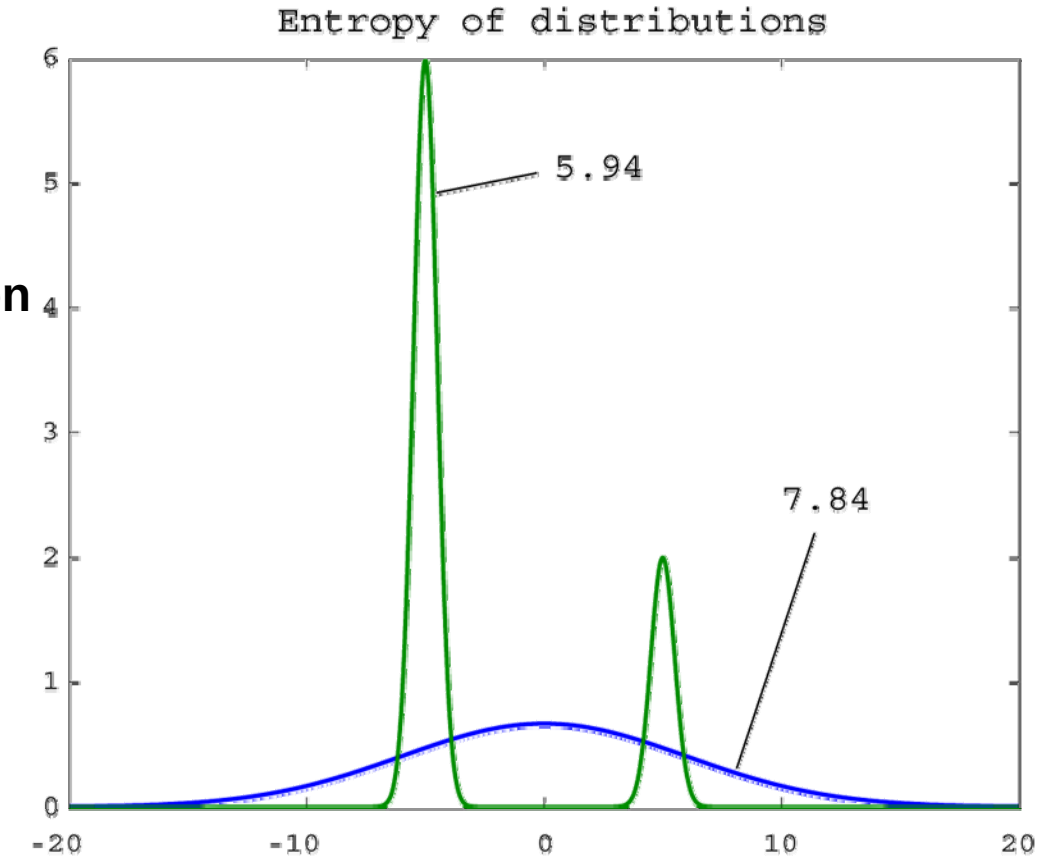
"entropy of echo power (scatter) distribution"

- 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**



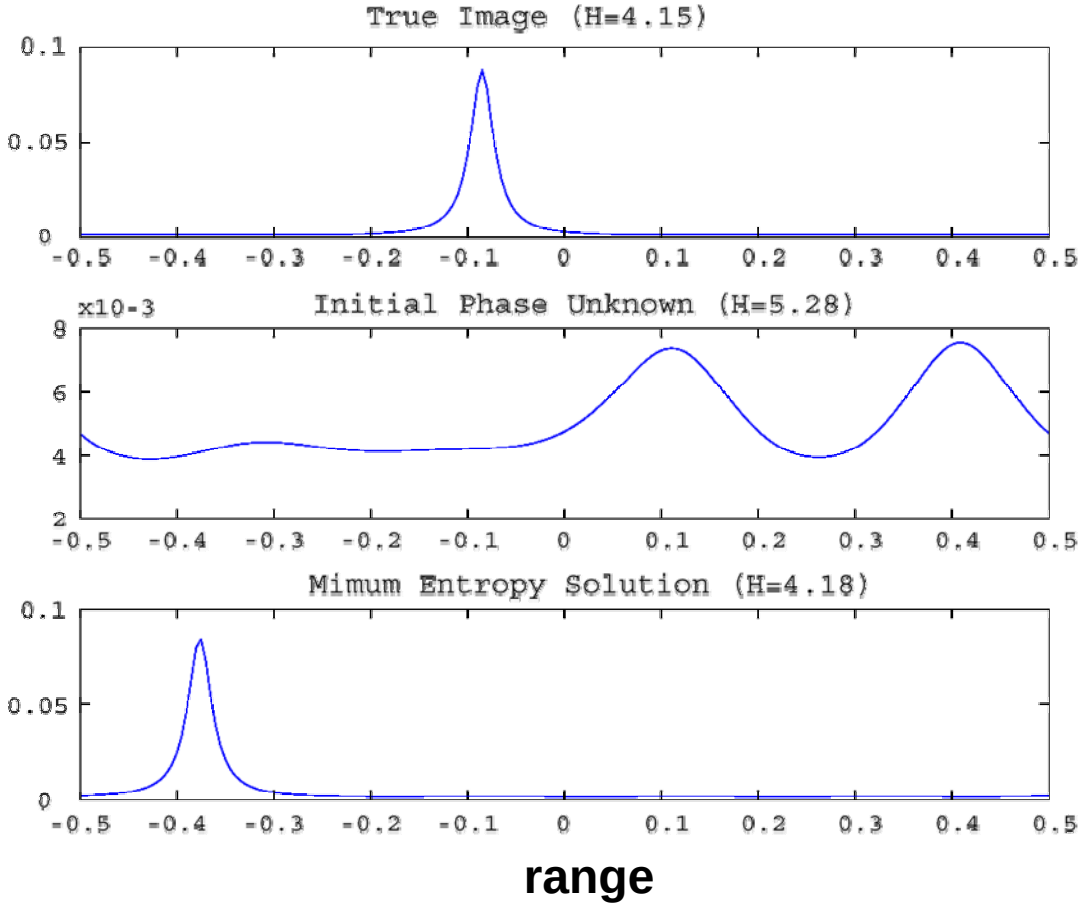
minimum entropy solution of unknown eigen (initial) phases

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

known eigen phases
(true image)

random solution
(ignore eigen phases)

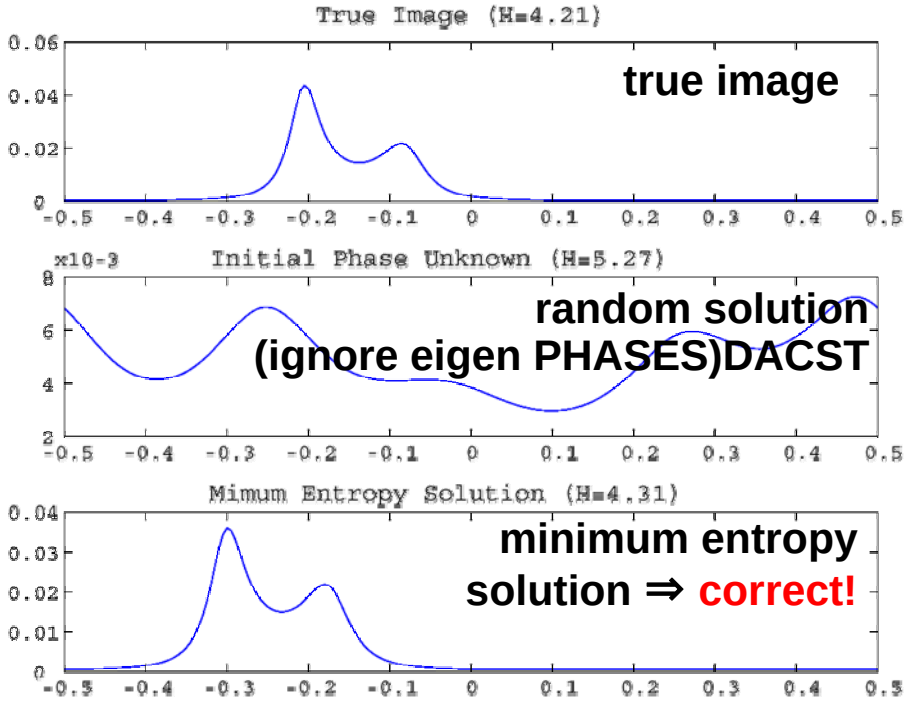
minimum entropy solution
⇒ correct solution!
except relative range offset

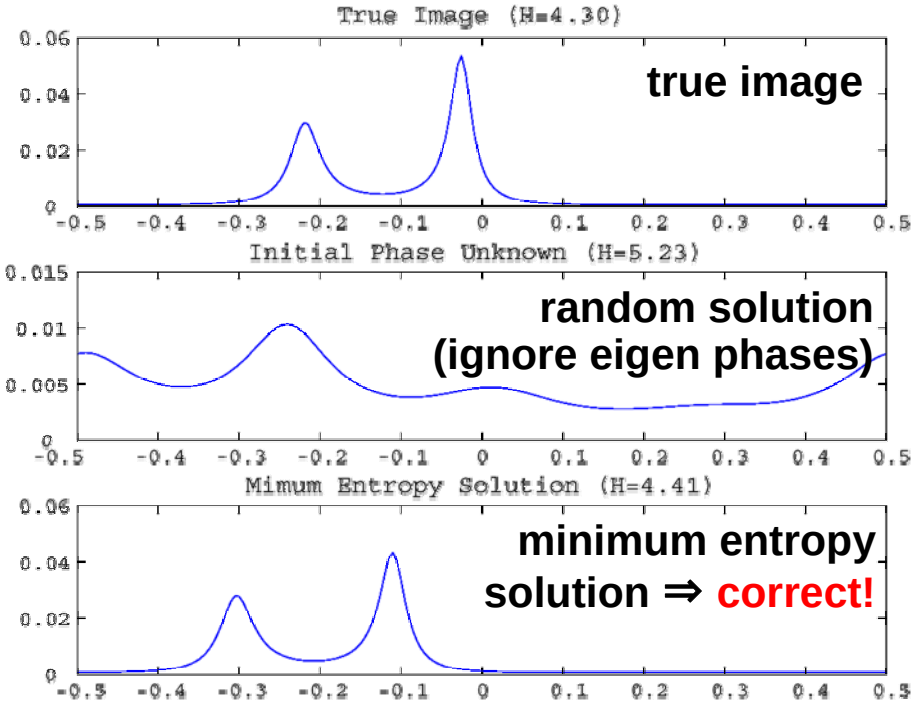


minimum entropy solution of unknown eigen (initial) phases

- 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 results

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

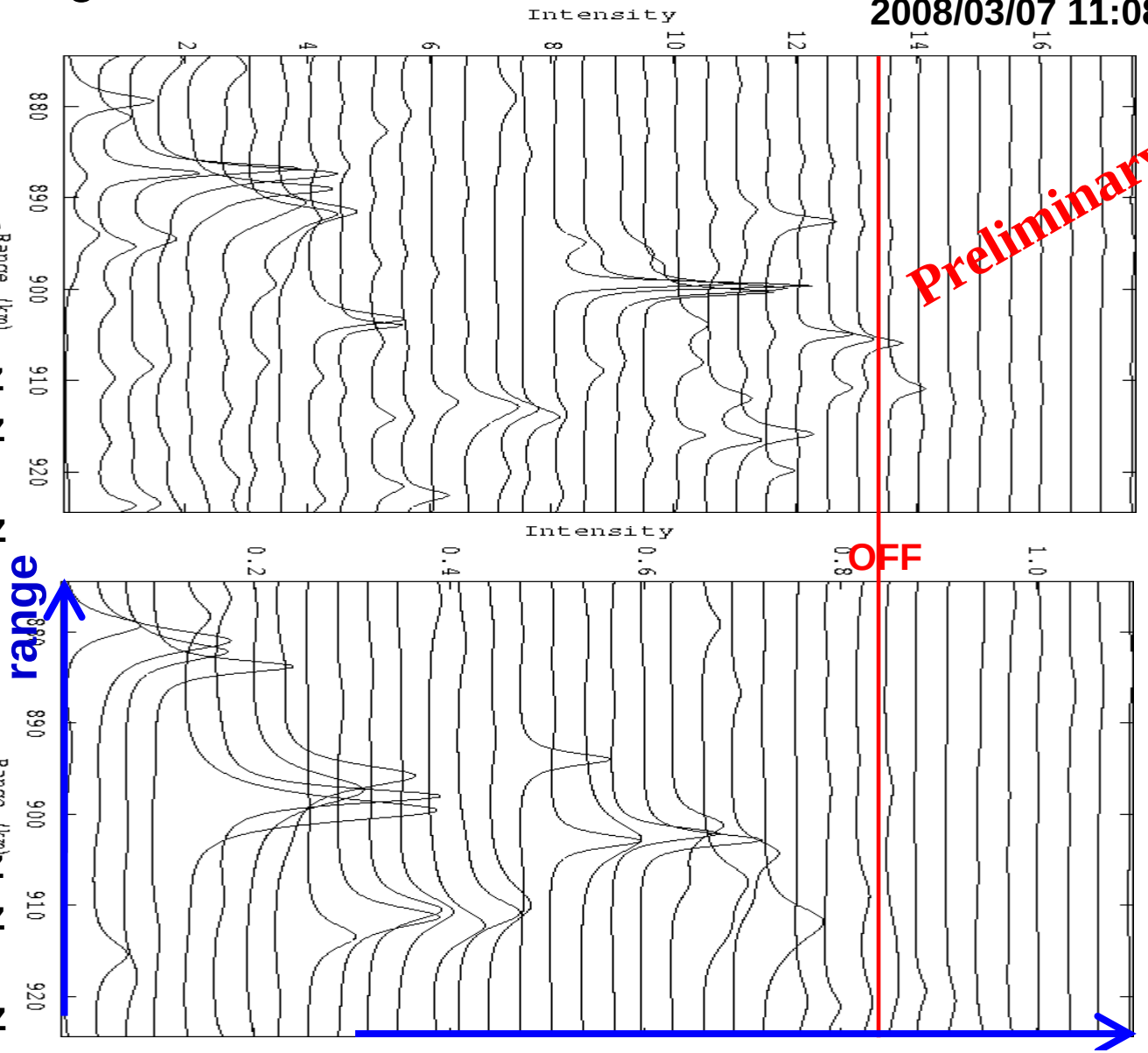
2008/03/07 11:08-11:09

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



Preliminary Results

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

Summary & Future

- tried to review SuperDARN mono/stereo radar systems, analogue/digital Rx systems, and various techniques to improve spatial resolution for both beam/azimuth and range directions (SDI & FDI) including "imaging" techniques.
- To improve azimuth resolution, adaptive beam forming (or SDI imaging) technique is promising. A SD group already started operation. Syowa radar(s) will also try to implement it (under development).
- To improve range resolution, FDI technique was tried. At least near range FDI was successful using meteor echoes. However, for farther ranges, difficulties still remain (possibly due to basic problem). Pulse/phase coding technique will be promising though radio authority license issue needs to be renewed/solved.
- Using higher spatial resolution techniques with new digital Rx capabilities as well as higher temporal resolution technique (raw IQ time series TMS techniques), many new scientific researches are expected also for mid-latitude SD radars.