量子アルゴリズムを用いた先進非破壊評価法の検討

群馬大学大学院理工学府　環境創生部門

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自己紹介(1)

Assoc. Prof. Takahiro SAITOH
2006: Dr.(Eng.)
from Tokyo Institute of Technology, Japan

2023: IPA未踏ターゲット事業プロジェクト修了
（量子コンピュータを用いたソフトウェア開発分野）

My biography:

- Mar., 2006, Dr. of Engineering, Tokyo Institute of Technology（東工大）
- Apr., 2006：Japan Society of Postdoctoral Fellowship（学振）
- Nov., 2008：Assis. Prof., at Fukui University（福井大）
- Oct., 2009：Assis. Prof., at Dept. Tokyo Institute of Technology（東工大）
- Aug.,2010: Visiting researcher, Siegen University, Germany (ドイツ，Siegen大学)
- Apr., 2012：Assoc. Prof., at Gunma University (群馬大)

Academic society affiliation：

- JSCE: Japan Society of Civil Engineers（土木学会）
- JSME: Japan Society of Mechanical Engineers（機械学会）
- JSCES: Japan Society for Computational Engineers（計算工学会）
- JASCOME: Japan Society for Computational Methods in Engineering（計算数理）
- JSST: Japan Society for Simulation Technology（シミュレーション）
- JSNDI: Japan Society for Non-Destructive Inspection（非破壊検査）

自己紹介(2)-専門分野と主な最近のプロジェクト

応用力学・計算力学に関する研究

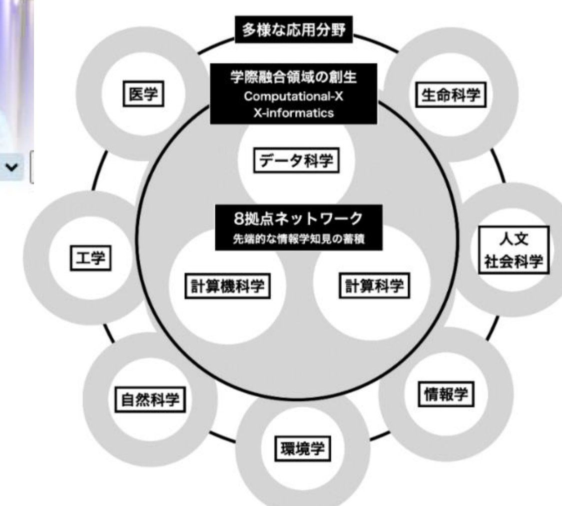
- 2024～非局所理論の非破壊評価への展開（科研費基盤研究(B), 代表)

弾性波動論，非破壊評価に関する研究（数値計算が柱）

- 2024～時間反転法を用いた鋼床板中の疲労き裂検出のためのDX超音波非破壊検査の開発（財）高速道路調査会，代表)
- 2025～量子アルゴリズムを用いたコンクリート非破壊検査のための新たなトモグラフィ理論の検討（前田記念工学振興財団，代表)

計算力学・計算数理・シミュレーションに関する研究

スパコンの事業（JHPCN）

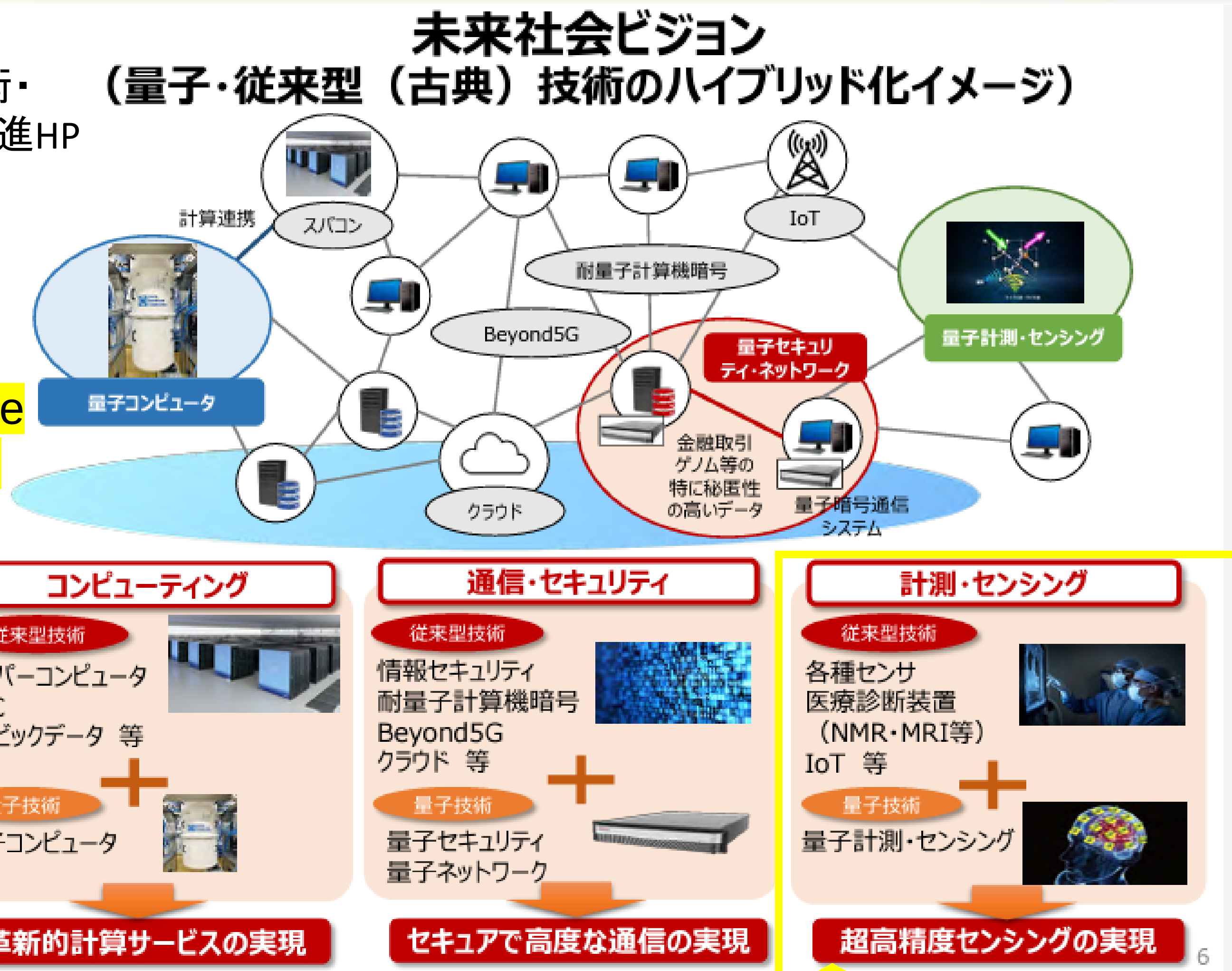


- 2014～ずっと：NDE4.0実現のための高性能波動解析技術とデータサイエンスの融合（東工大，京大，代表）

NDE4.0: 第4世代非破壊評価（AI, ビッグデータ, センシング，HPC）

量子コンピューター活用への期待

(内閣府科学技術・イノベーション推進HPより引用)



High-Performance Computing(HPC)
JHPCNと連携？

計測をしてその後どうするか？
何のための計測か？

非破壊検査

計算力学分野では量子コンピューター活用への期待が高まっている
（量子コンピューターを用いた新たな展開）

What is NDT (Non-Destructive Testing) ?

Non-destructive testing is the method to examine structures and materials without damaging or destroying the object being tested, and to ensure their reliability and quality

Fig.1: 建設後50年後の橋梁の数

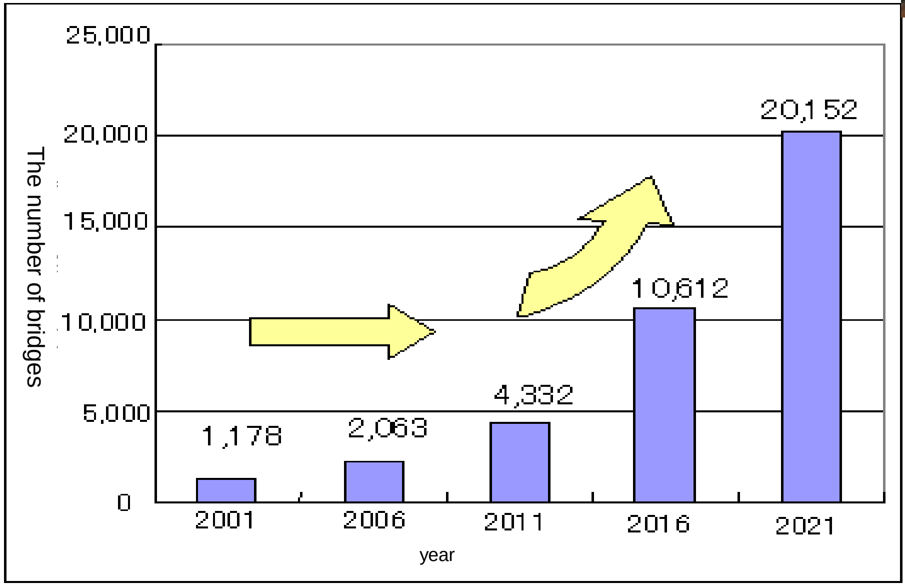
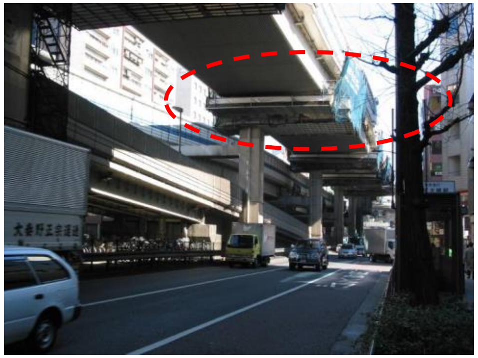


Fig.3: Sasago tunnel collapse (2012)

Fig.2: Fatigue damage of corner intersection for a steel bridge

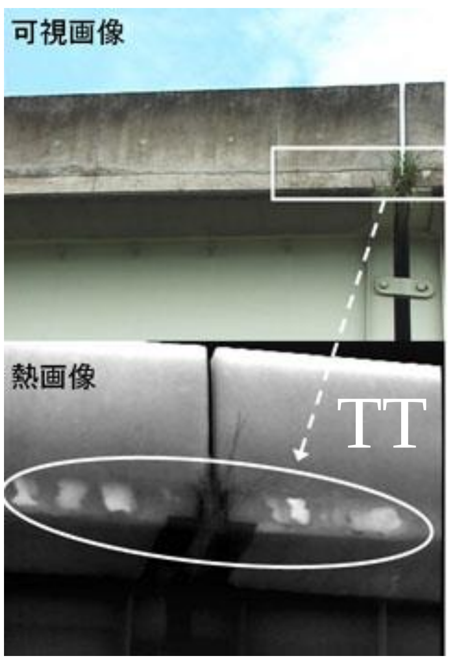


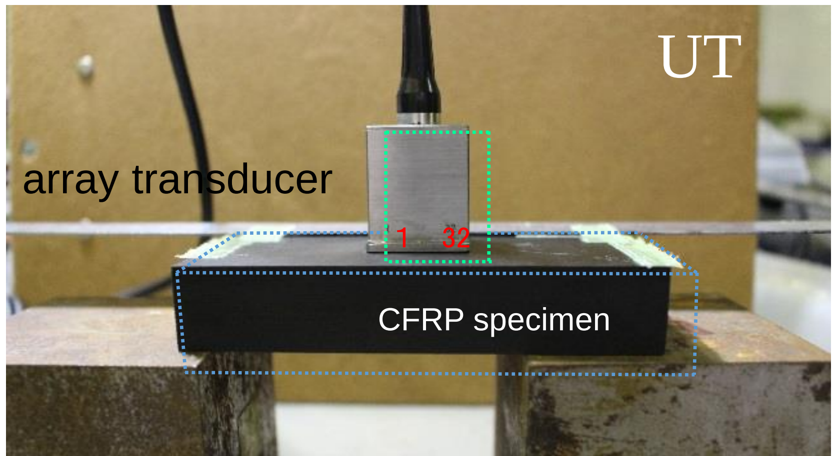
最近の埼玉県八潮市の道路陥没はまさにインフラ維持管理と非破壊検査に関する大きな問題

様々な非破壊評価

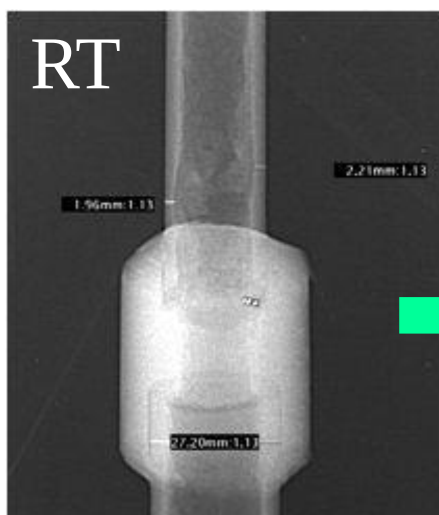
様々な非破壊検査手法が提案されてきた

- 目視点検(VT)
- サーモグラフィー試験 (TT)
- 放射線透過試験(RT)
- 超音波試験，レーザ超音波試験(UT)
- 渦電流探傷試験(ET)





医療の診断と同じ概念
医者が患者を診断し
適切な評価を下すのと
同様のことを，構造・
材料に対しても実施する

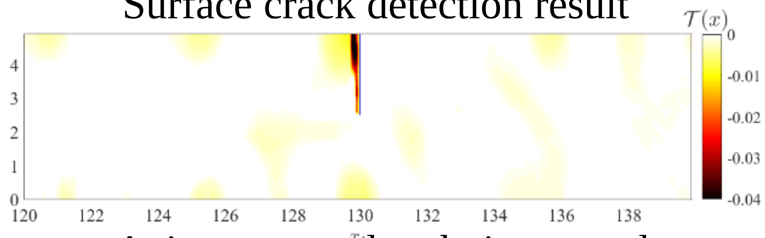


非破壊評価の最終目的

The main goal of non-destructive testing is to identify the presence, size, and shape of defects
Therefore, various inverse analysis methods have been proposed to improve defect detection
（非破壊検査の問題は最終的に欠陥や材料等を推定する逆問題に帰着される）

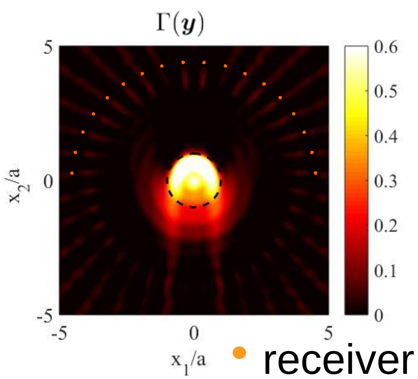
- Synthetic Aperture Focusing Technique (SAFT)
- Born or Kirchhoff approximation based inverse scattering techniques
- Time-reversal techniques
- Computed Tomography techniques (CT) (計算トモグラフィ)

Surface crack detection result



A time-reversal technique result

A Born-based inverse scattering result



• receiver point

- G. N. Hounsfield, Computerized transverse axial scanning (tomography): Part 1. Description of system, British Journal of Radiology 46 (552), 1 December 1973, pp.1016{1022, doi:10.1259/0007-1285-46-552-1016.
- G. N. Hounsfield, Computed medical imaging. Science. 1980 Oct 3; 210(4465), pp.22-28, doi: 10.1126/science.6997993. PMID: 6997993.

現在のCT（Computed Tomography）を提案

診断結果を
得るまでの時間は
長いが
実用化に至っている

CT装置の例:群馬大学医学部より

THE NOBEL PRIZE

ノーベル賞HPより

Nobel Prizes & laureates　About　Stories　Educational　Events & museums

1979年：ノーベル生理学・医学賞を受賞

Godfrey N. Hounsfield

Biographical　（イギリスの電子技術者）

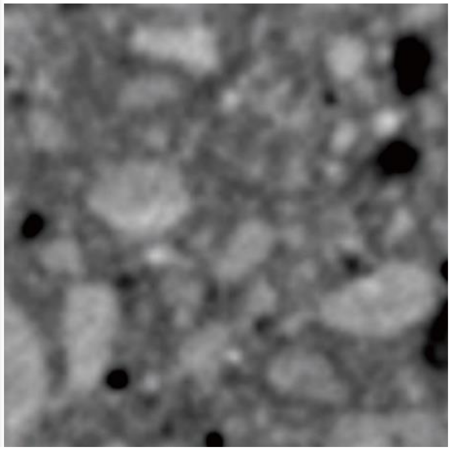
I was born and brought up near a village in Nottinghamshire and in my childhood enjoyed the freedom of the rather isolated country life. After the first world war, my father had bought a small farm, which became a marvellous playground for his five children. My two brothers and two sisters were all older than I and, as they naturally pursued their own more adult interests, this gave me the advantage of not being expected to join in, so I could go off and follow my own inclinations.

The farm offered an infinite variety of ways to do this. At a very early age I became intrigued by all the mechanical and electrical gadgets which even then could be found on a farm; the threshing machines, the binders, the generators. But the period between my eleventh and eighteenth years remains the most vivid in my memory because this was the time of my first attempts at experimentation, which might never have been made had I lived in a city. In a village there are few distractions and no pressures to join in at a ball game or go to the cinema, and I was free to follow the trail of any interesting idea that came my way. I constructed electrical recording machines; I made hazardous investigations of the principles of flight, launching myself from the tops of

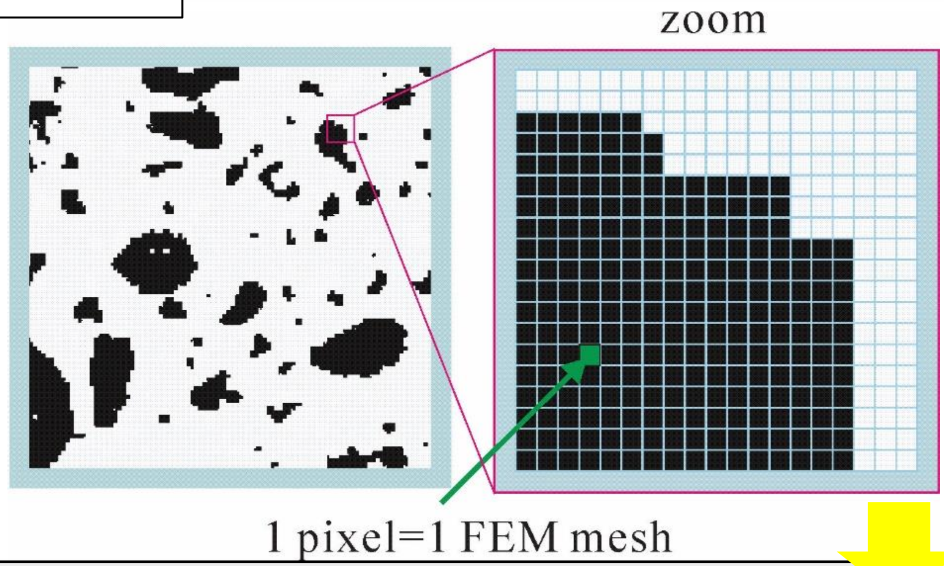
Various tomography theories(2)

□ 構造材料とイメージベースモデリング（コンクリートの場合）

イメージベースモデリング



コンクリートX線CT画像



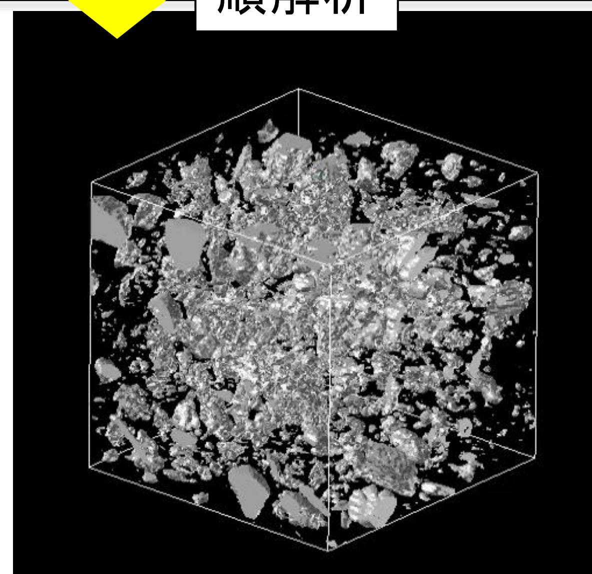
画像の階調で母材や骨材を区別

画素数：200×200

母材の閾値：0～60

骨材の閾値：61～255

順解析



□ 構造材料の中身がわからなければ順解析はできない

Flaw detection in nondestructive testing

□ E. Bazulin, A. Goncharsky, S. Romanov, S. Seryozhnikov, Ultrasound transmission and reflection tomography for nondestructive testing using experimental data, Ultrasonics 124, 2022, 106765, doi :10.1016/j.ultras.2022.106765.

Objective

In preparation for the future practical implementation of quantum computers, it is important to develop quantum algorithms that can be utilized in the non-destructive evaluation field from now

We try to develop a quantum algorithm based computed tomography (CT) technique
(CTアルゴリズムの再検討)

- Use a quantum annealing simulator
- Aim to develop quantum algorithms specifically designed for quantum computers

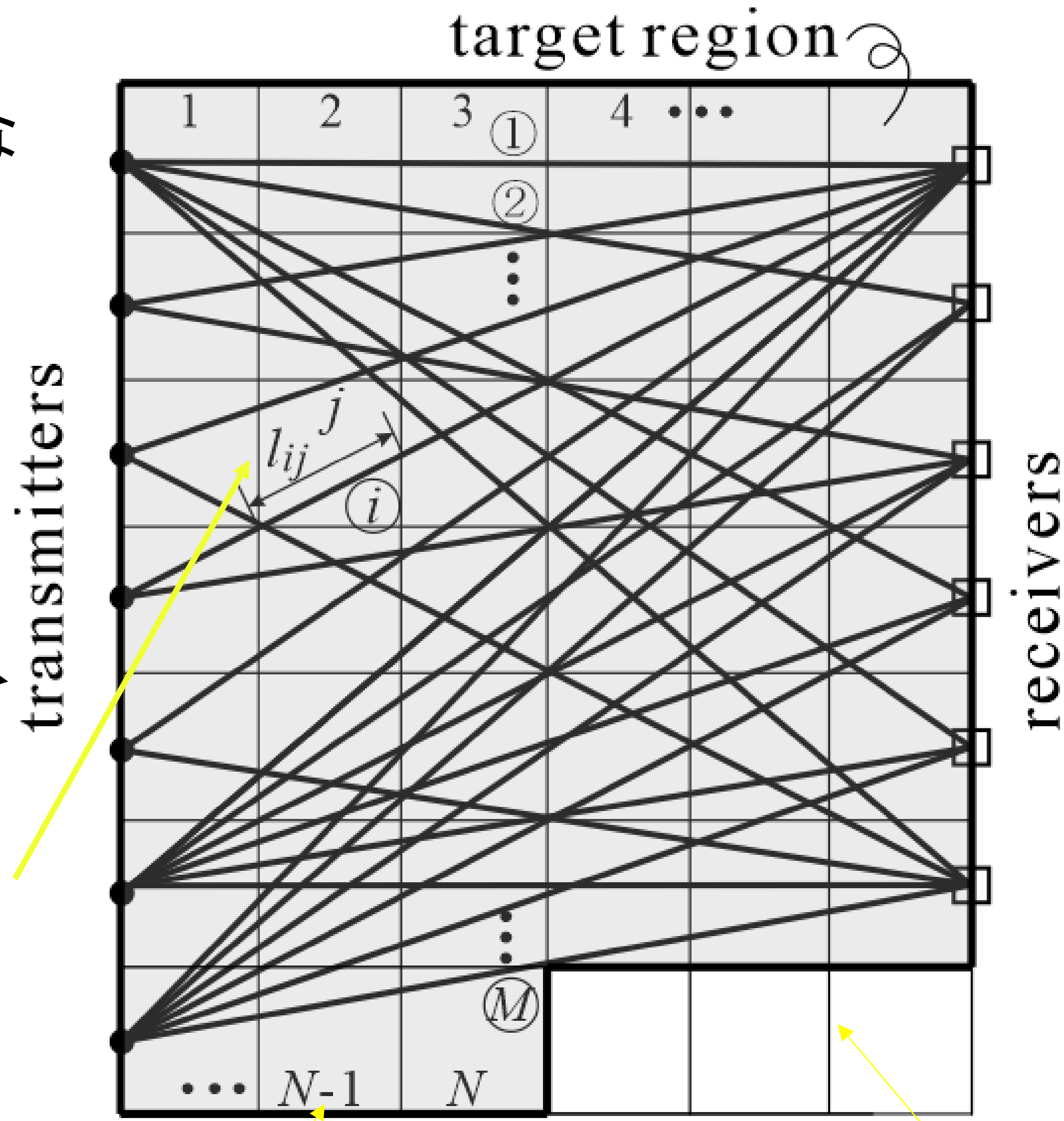
In the following slides, the properties of quantum computers and the analysis results of the quantum algorithm-based CT proposed in this research are demonstrated

Computed Tomography (CT) algorithm

問題の設定
(反射等を考えない最も単純な場合を考える)

光やX線等の波動等の送信領域を設定

i番目のpassがsub領域jを通過する線分



受信領域

分割領域(subregion)

波線(トラベルpass)

Computed Tomography (CT) algorithm

The travel time t_i along the ⓘ-th ray path is expressed as

$$t_i = \sum_{j=1}^{N} l_{ij} s_j \quad (i = 1, \ldots, M), \quad \text{or} \quad \boldsymbol{t} = \boldsymbol{l}\boldsymbol{s}$$

(ray-path Eq.)

s_j: slowness in *j-th* subregion l_{ij}: line segment of the ⓘ-th ray path

$M = N$ → Slowness s_j can be calculated by $\boldsymbol{s} = \boldsymbol{l}^{-1}\boldsymbol{t}$

$M \neq N$ → The problem is reduced to the optimization problem such as

波線の数

$$\hat{\boldsymbol{s}} = \arg\min_{\boldsymbol{s}} \frac{1}{2} ||\boldsymbol{t} - \boldsymbol{l}\boldsymbol{s}||_2^2. \quad M > N$$

Sub領域の数

$$\hat{\boldsymbol{s}} = \arg\min_{\boldsymbol{s}} \frac{1}{2} ||\boldsymbol{t} - \boldsymbol{l}\boldsymbol{s}||_2^2 + \lambda ||\boldsymbol{s}||_1, \quad M < N$$

In short, the computed tomography (CT) problem can be reduced to an optimization problem that minimized the residual of the ray-path integral equation

Quantum annealing requires that the problem to be solved is formulated in the QUBO (Quadratic Unconstrained Binary Optimization) format as shown in

$$f(b) := \sum_{i,j=1}^{N} Q_{ij} b_i b_j$$

binary value

Ray-pass optimization problem considered in this research can be rewritten as

$$||\boldsymbol{t} - \boldsymbol{ls}||_2^2 = \sum_{k=1}^{M} \left(\sum_{j=1}^{N} l_{kj} s_j - t_k \right)^2 = \sum_{k=1}^{M} \left(\sum_{j=1}^{N} \sum_{i=1}^{N} l_{ki} l_{kj} s_i s_j - 2b_k \sum_{j=1}^{N} l_{kj} s_j + t_k^2 \right)$$

$$= \left[\sum_{j=1}^{N} \sum_{i=1}^{N} \left(\sum_{k=1}^{M} l_{ki} l_{kj} \right) s_i s_j - \sum_{j=1}^{N} \left(\sum_{k=1}^{M} 2b_k l_{kj} \right) s_j + t_k^2 \right]$$

$$= \left[\sum_{i,j=1}^{N} L_{ij} S_i S_j + \sum_{j}^{N} L_{jj} S_j + t_k^2 \right] = \sum_{i,j}^{N} Q_{ij} S_i S_j$$

function of binary value

Since the ray pass optimization problem was successfully formulated in the QUBO format, the optimized combination of slowness can be obtained using quantum annealing computation

- As Qubo annealing, Torch Tytan is used as “quantum simulator”

(A quantum simulator is a controllable quantum system designed to model and study the behavior of complex quantum systems that are difficult to simulate with classical computers)

- In quantum annealing, numerical solutions are obtained probabilistically by using quantum mechanics

Therefore, in quantum computers, the same computation is executed multiple times, which is called the number of shots, to estimate the true solution

Therefore, the following two types of results are presented

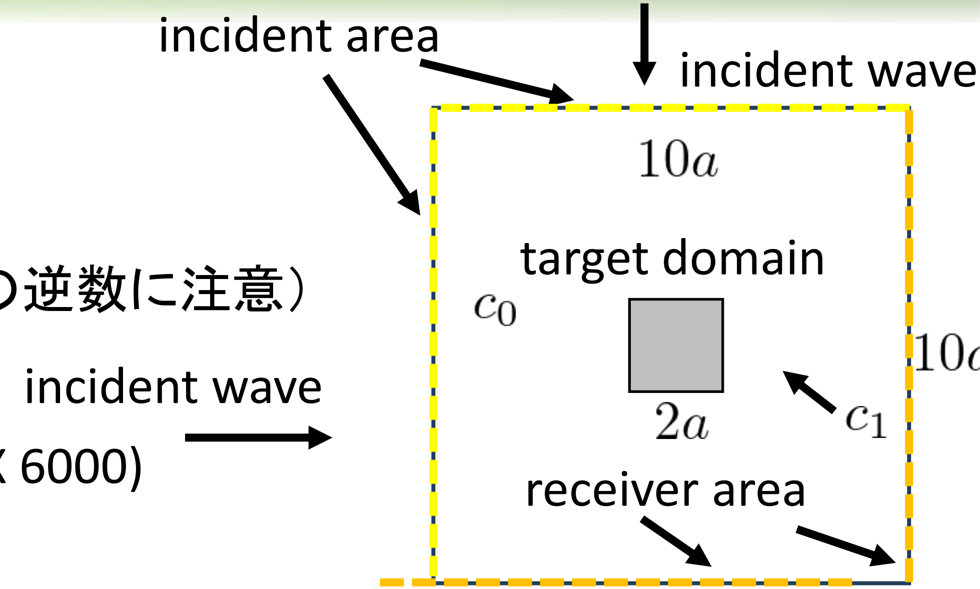
- 材料種別が2つだけ(0,1だけのbinary表現で十分な問題)
- 材料種別が3つの問題 (one hot 制約が必要な問題)

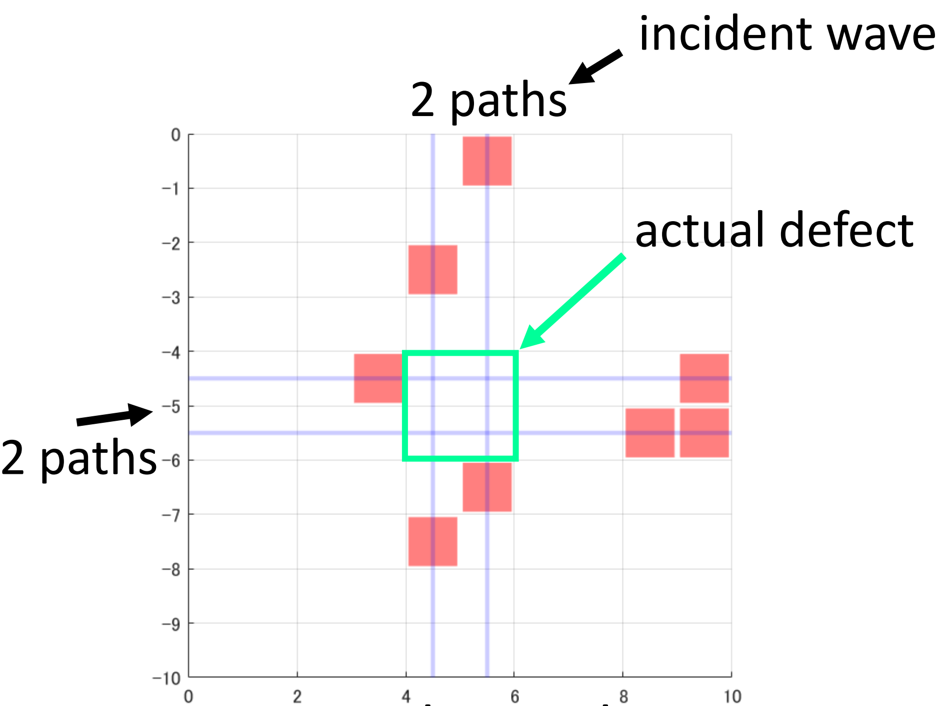
トモグラフィ基礎検討結果(1)

欠陥部分(矩形欠陥)を逆解析

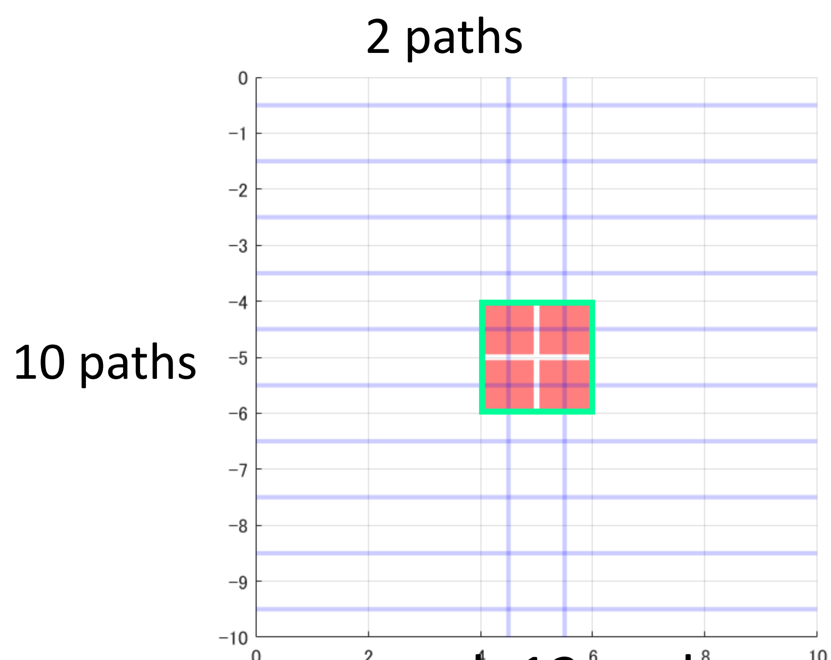
送受信領域限定(ただし形上)
波動の到達時間(光強度)を制約条件
無次元化slowness: $s_0 = 2.0 s_1$(速度の逆数に注意)
ショット数:10000

Qubo アニーリング(Torch Tytan, GPU:RTX 6000)





total: 4 paths



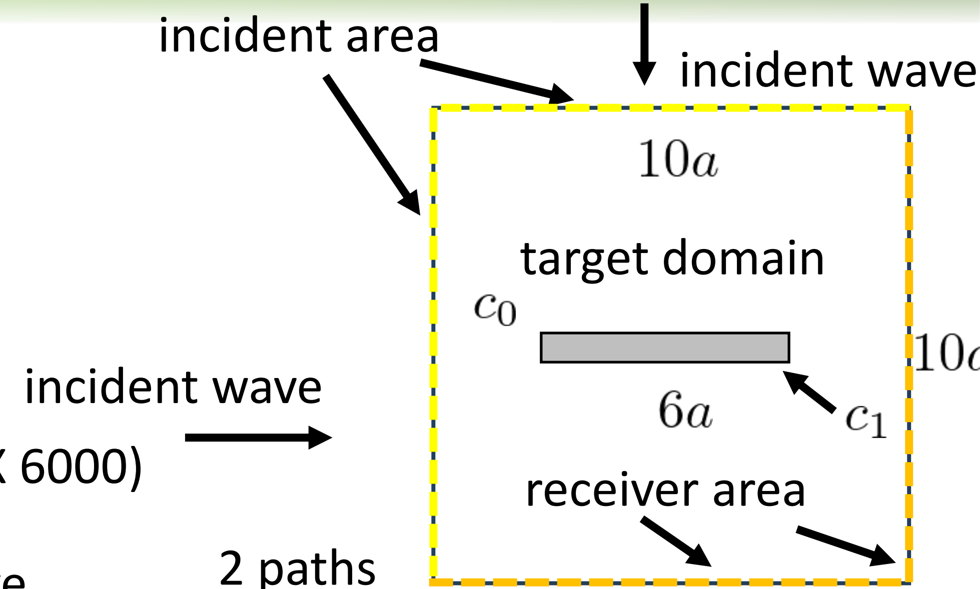
total: 12 paths

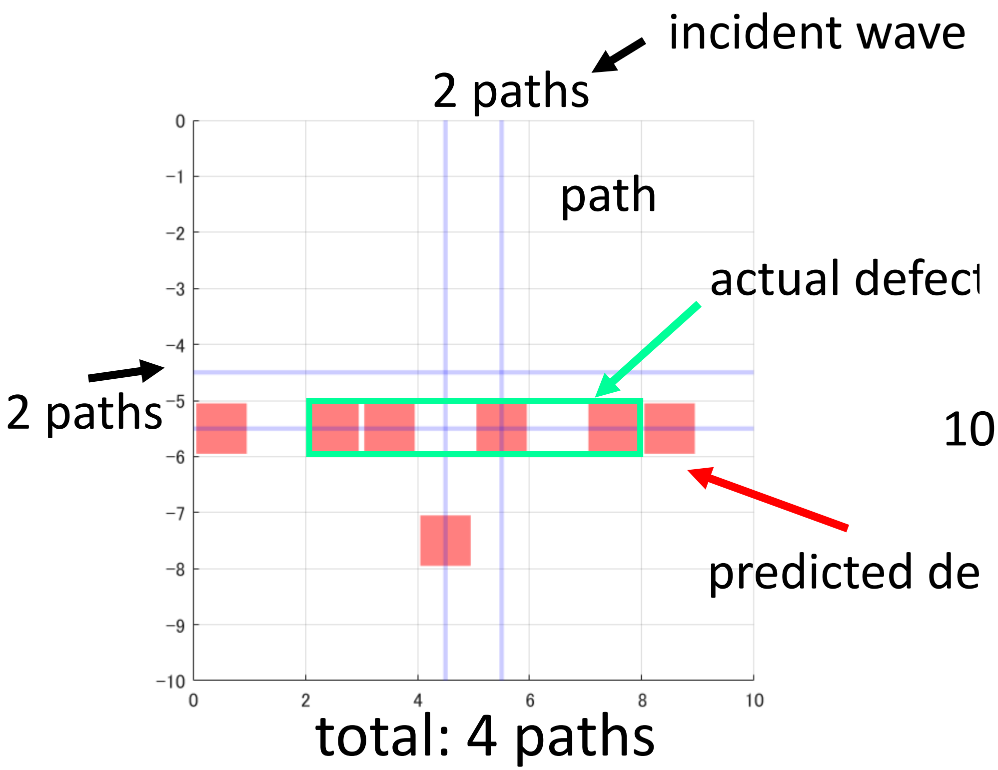
トモグラフィ基礎検討結果(2)

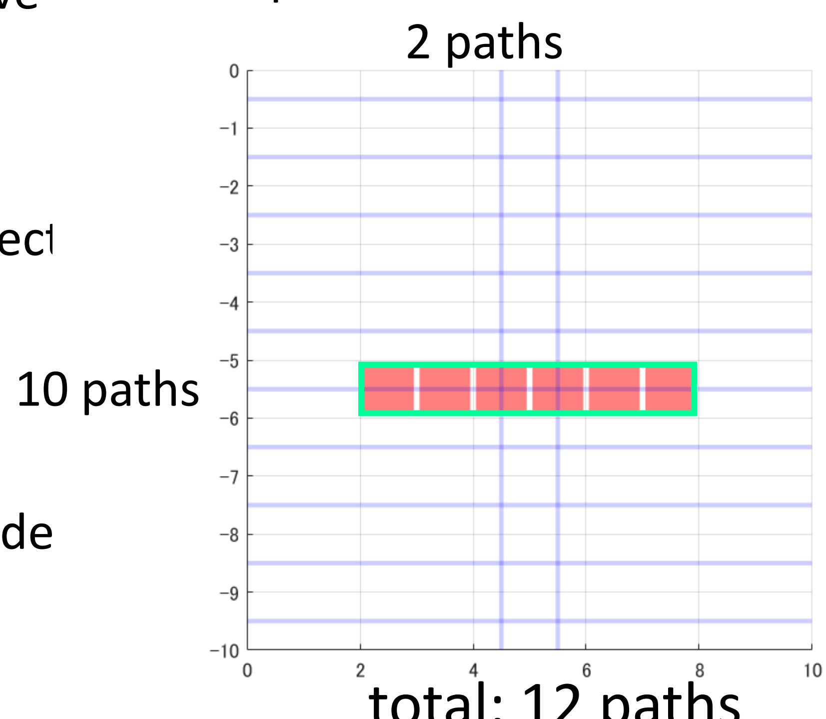
欠陥部分(スリット)を逆解析

送受信領域限定(ただし形上)
波動の到達時間(光強度)を制約条件
無次元化slowness: $s_0 = 2.0 s_1$
ショット数:10000

Qubo アニーリング(Torch Tytan, GPU:RTX 6000)







まとめと今後の課題・予定

まとめ

- 量子アニーリングの考え方からトモグラフィ理論の再検討を行った
- 基礎的な問題ではあるが，one-hot制約やtravel timeの制約を用いて欠陥形状を再構成することができた
- 十分な制約条件下であれば欠陥形状を再構成できることを示した

今後の課題・予定

- 3次元解析への応用
- 材料種別が増えた場合の詳細な検討
- 反射トモグラフィへの応用
- 特性関数を導入するタイプの非線形逆解析等への応用
- 実際の計測データを用いた場合の検討