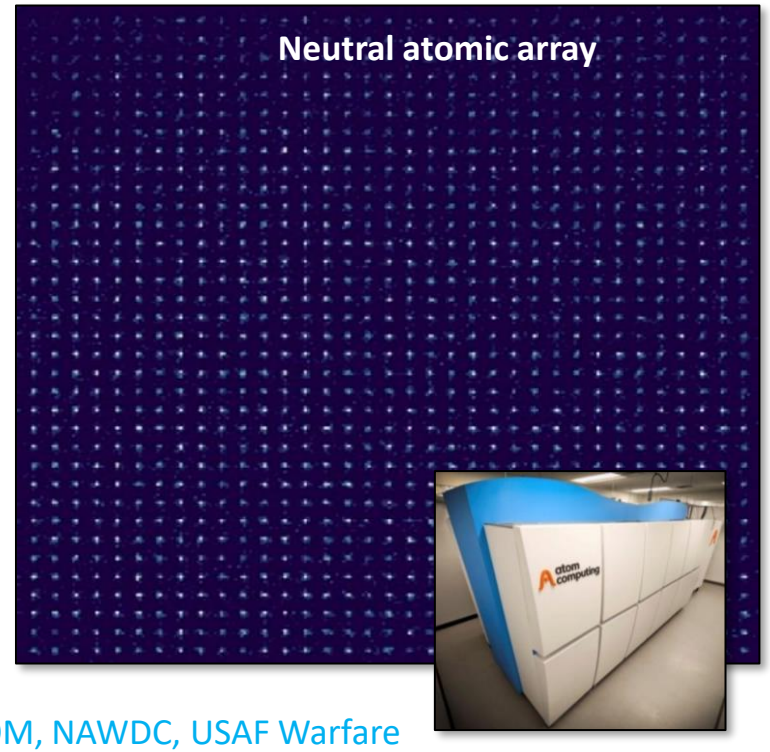
This software will make Air Battle Management Systems (ABMS) at least 28% more efficient*

OUR TECH SOLVES THIS NEED:
Classical computing does not have the processing capability for the massive multi-variate computations needed for optimized ABMS resource utilization.

- This submission team (QRS, Purdue University, Air Force Institute of Technology (AFIT) and Atom Computing) will perform the research and obtain the stakeholder input to develop a resource utilization optimization software using a 1000+ qubit neutral atom quantum computer.
- This software will provide the AF with a dramatically faster and more accurate ability to manage, coordinate and schedule friendly force ("blue") assets.
- PACAF/613 AOC will collaborate with us to design, develop and launch this tech. LOS is attached.



- This software can be integrated with PEO's delivering JADC2 and extended to STRATCOM, TRANSCOM, NAWDC, USAF Warfare Center, etc. Commercialization will start with defense corp's that are building the next generation of ABMS. Total market size is $11B.
- Quantum Research Sciences (QRS) is the only company to produce and deliver an operational, production-level (Phase III) Quantum Computing software to the DoD; which was accomplished via a prior USAF STTR Open Topic (AF20C-TCS01). Best practices & lessons learned from that STTR and Phase 3 transition will be applied to this effort.

*** 28% IS THE LEVEL OF IMPROVEMENT ACHIEVED VIA OUR CURRENT USAF QUANTUM SUPPLY CHAIN TECHNOLOGY**

This software will enable PACAF to optimize resource utilization within ABMS and Battle Management Command and Control (BMC2)

- The only available capability to deliver a dynamic and comprehensive friendly force asset optimization of this complexity is with quantum technology.

A

Quantum-based software will be exponentially faster than classical tools (while also being more accurate) because we will harness 2 quantum mechanical phenomena (superposition & entanglement)

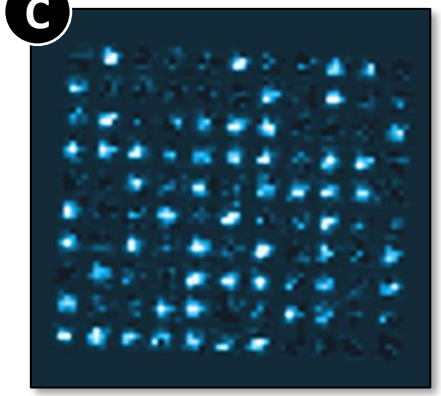
Please see Technical Merit Page 3 of 3

B

Superposition
Qubits hold multiple states at once

Entanglement
States of multiple qubits tightly linked

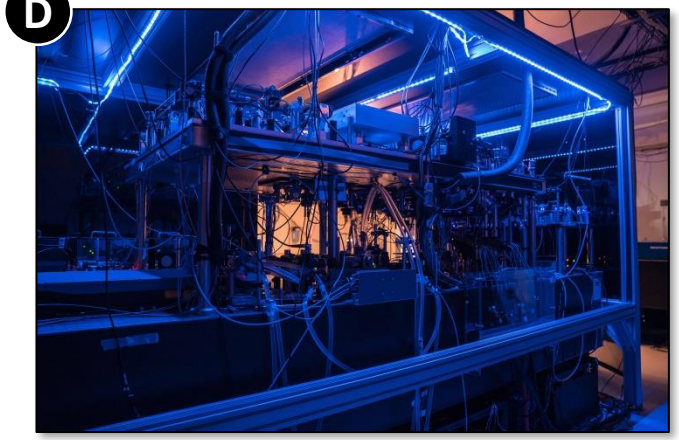
C



Atomic array

Please see Technical Merit Page 2 of 4

D



Neutral atom computer

Please see Transition Page for details on this step

E

Integration into existing systems

Neutral atom technology is a path to the expansive resource optimization needed by PACAF for ABMS

QUANTUM COMPUTER TYPES

Superconducting
IBM
Google
Rigetti

Neutral Atom
Atom Computing
ColdQuanta
Pasqal

Trapped Ion
IonQ
Quantinuum
AQT

Photonic
Xanadu
PsiQuantum

Quantum Dot
Intel

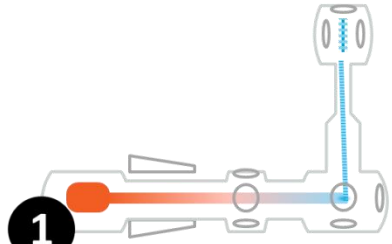
Color Center
Quantum Brilliance

Electron-on-Helium
EeroQ

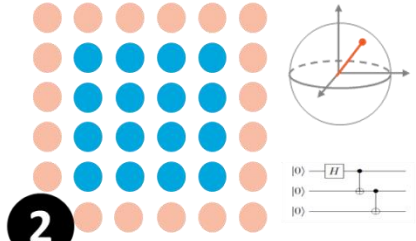
Silicon Spin
Silicon Quantum Computing

Topological
Microsoft

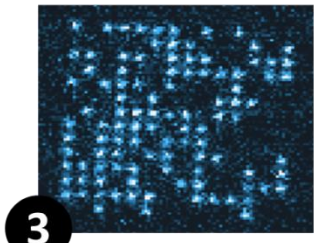
Exceptional optimization capability



1 PREPARING THE ATOMS
Hot stream of atoms cooled & optically trapped in 2D array

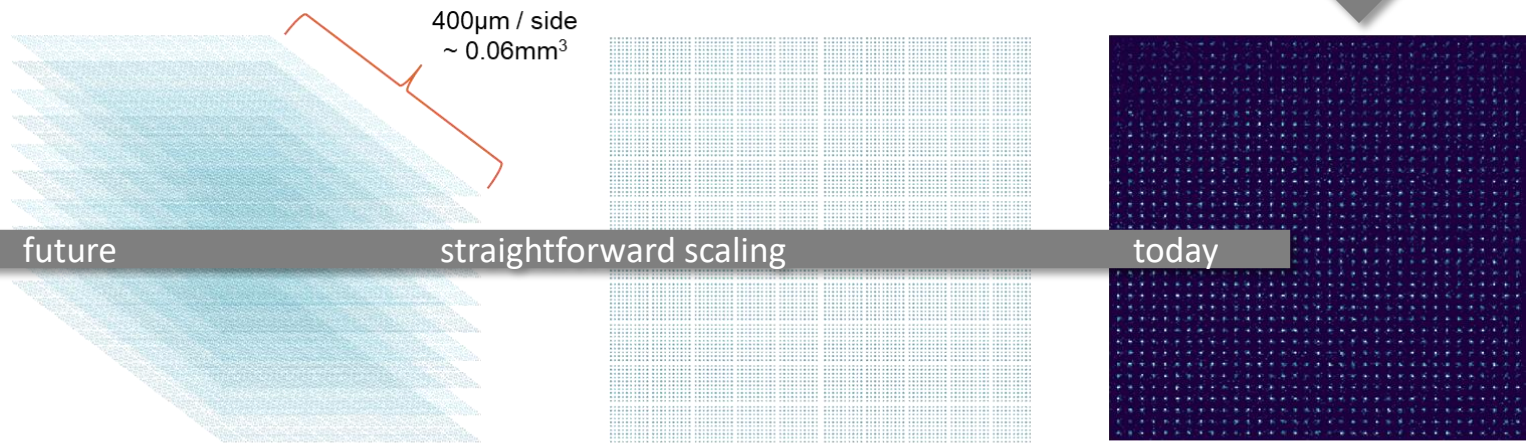


2 QUANTUM PROCESSING
Quantum gates are performed with sequences of laser pulses



3 RESULTS READOUT
Camera watches glowing qubits to identify 0's & 1's

Demonstrated growth



Comprehensive USAF resource utilization

Below equation (and its variations) is one of the most realistic and complex friendly force asset optimizations at any given point in time [1 – 4]

- Asset allocation quantum code will be developed with the objective function proposed below, which does not simplify costs or constraints.
- To quickly deliver automated solutions temporally (e.g., re-assignment of assets, evolving situation, off-axis, etc.), the same equation can be nearly instantaneously recalculated while Battle Management Command and Control (BMC2) needs are changing.

Hamiltonian

$H = (H_P + H_T - B)^2 + H_O + H_{RO} + H_{BC} + H_{TC}$

- $H_O = opportunity\ costs$
- $H_P = procurement\ costs$
- $H_T = transportation\ costs$
- $B = budget$
- $H_{RO} = running - out\ cost$
- $H_{BC} = battle\ constraint$
- $H_{TC} = transportation\ constraint$

Solution Space

Requirements:

- $n\ Assets$
- $m\ bases$
- $l\ qubits\ in\ bitstring$
- $T\ timesteps$

- $2nmlT + \frac{m^2-m}{2} n(l+1)T\ qubits$
- $2^{2nmlT + \frac{m^2-m}{2} n(l+1)T}\ number\ of\ solutions$

Inputs

- $s_{ij}\ (t)$ = $amount\ of\ i^{th}$ Asset $at\ j^{th}\ base\ at\ time\ t$
- $[\![d']\!]_{ij}\ (t)$ = $projected\ amount\ of\ demand\ for\ i^{th}$ Asset $at\ j^{th}\ base\ at\ time\ t$
- $d_{ij}\ (t)$ = $actual\ amount\ of\ demand\ for\ i^{th}$ Asset $at\ j^{th}\ base\ at\ time\ t$
- $D_{jj'}$ = $distance\ between\ base\ j\ and\ j'$
- C_R^{ij} = value of i^{th} Asset at j^{th} base
- C_P^{i} = $cost\ to\ buy\ i^{th}$ Asset
- C_S^{i} = $cost\ to$ transport i^{th} Asset $per\ distance$
- t_B = battle $lead\ time$
- t_P = $procurement\ lead\ time$
- t_T = transportation $lead\ time$

[1] Rossillon, K. , et al., (2015). *Optimized Air Asset Scheduling Within a Joint Aerospace Operations Center (JAOC).* [file:///E:/USAF%20STTR%2024D%20Phase%20I/P1%20USAF%20Docs/920696267-MIT.pdf]
[2] Allen, Charles (2002). *Air Tasking Order Dissemination: Does It Get The Job Done?* [https://apps.dtic.mil/sti/tr/pdf/ADA420267.pdf]
[3] Conner, Maj., et. al., (2005). *Analyzing The Air Operations Center (AOC) Air Tasking Order (ATO)…*, [https://apps.dtic.mil/sti/tr/pdf/ADA438397.pdf]
[4] Mak, M. (2023). *Battle Management.* [https://www.gao.gov/assets/gao-23-105495-highlights.pdf]

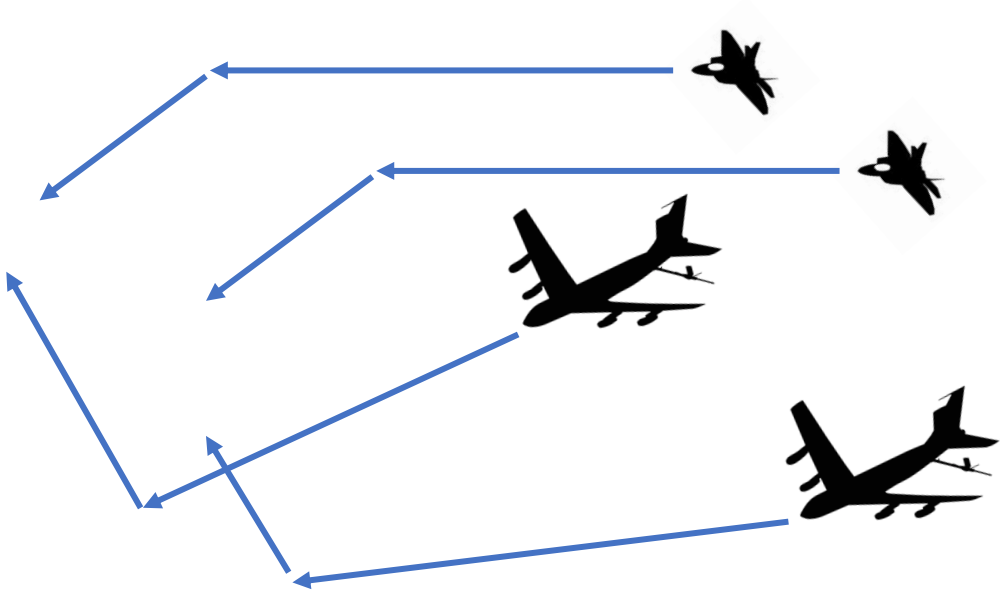
CONCEPT AND SIGNIFICANCE OF PROBLEM/OPPORTUNITY

Col. Gillaspie, Combat Ops Division, 613 AOC: "Today's technology inefficiently estimates where assets are needed and then updates infrequently. A dynamic optimization can much more effectively ensure assets are being allocated where the need will be."

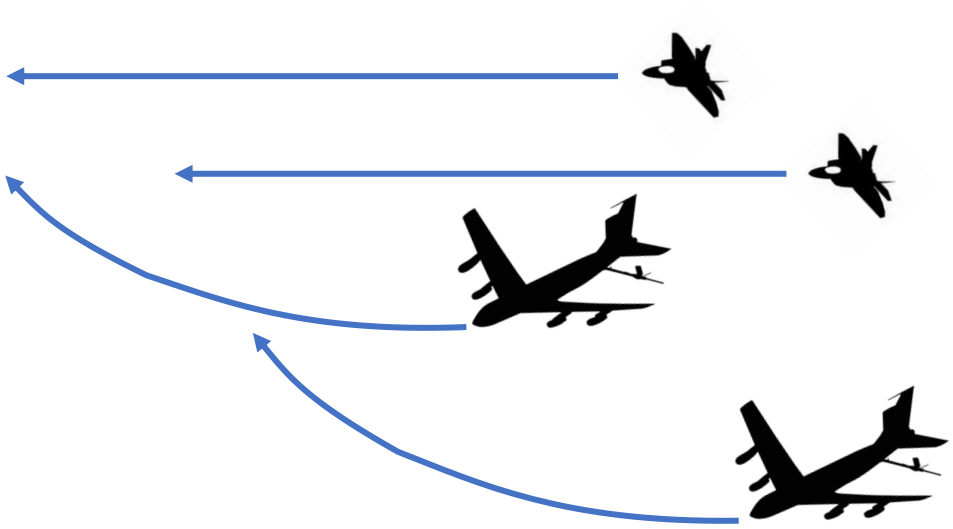
- Current Battle Management Command and Control (BMC2) tools yield a forced coordinated schedule. Human juggling still required. Process can take hours and output is only best effort.

Major Garcia – not thrilled with below graphics, but can't think of anything better. Any recommendations?

CURRENT TECHNOLOGY



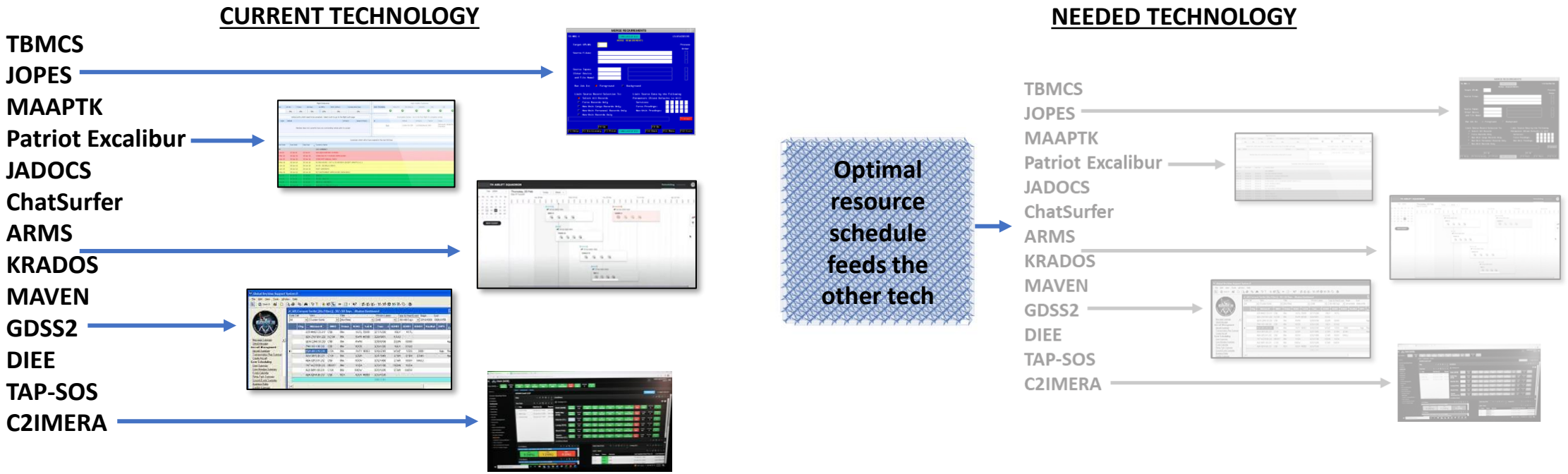
NEEDED TECHNOLOGY



Major Paul Garcia, PACAF 613 AOC Chief of Technology and Innovation: "F-22 operations shouldn't be constrained by spreadsheet scheduling."

- Current AF coordination and scheduling tools still involve static allocation spreadsheet ands communication applications.
- Real-world combat environments demand a dynamic approach because of multiple changing requirements and temporal expansions/contractions; all while there is the potential for physical or economic fluctuation of resources.

Major Garcia – same on this one…

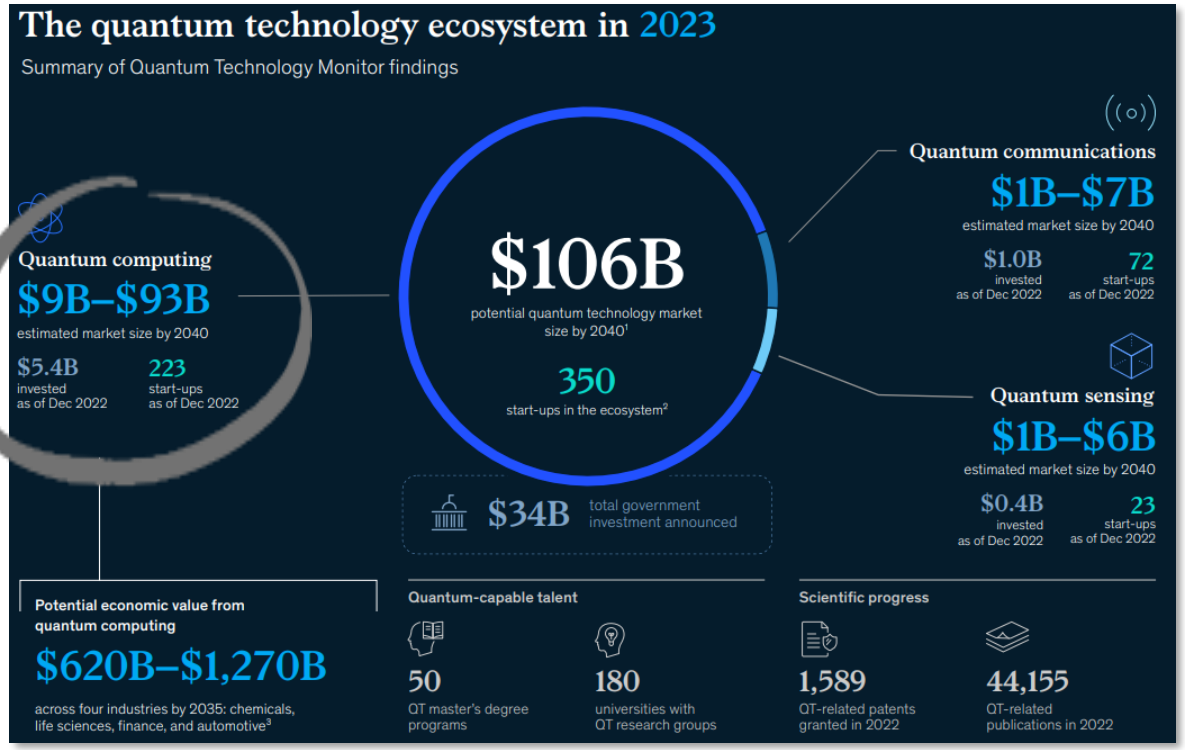


SUMMARY OF THE SOLUTION'S COMMERCIALIZATION POTENTIAL

Quantum computing is large and growing. Optimization has ~50% of that market potential. Asset optimization has immediate applicability to several industries. We'll start with Defense Corps and expand to other markets identified in this McKinsey study. McKinsey April '23.

Economic value + Incremental ++ Significant +++ Disruptive

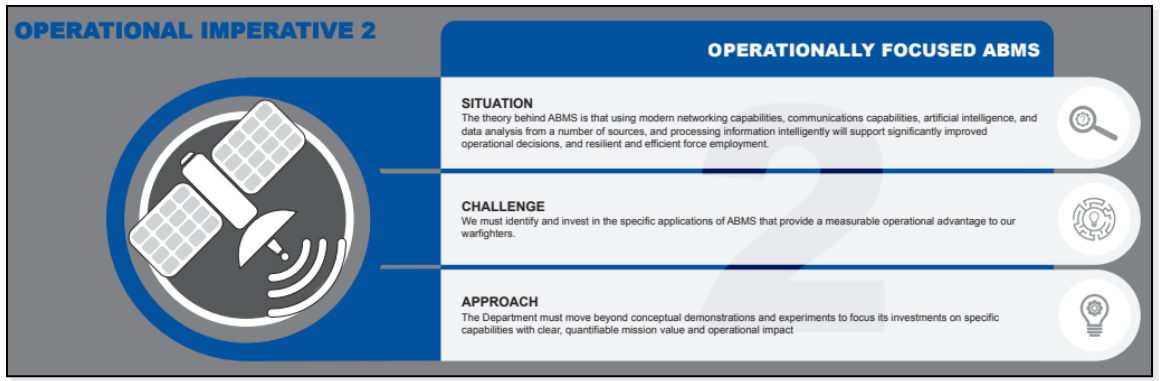
Industry	Key segment for QC	2025–30	2030–35
Global energy and materials	Oil and gas	+	++
	Sustainable energy	+	+++
	Chemicals	++	+++
Life sciences	Pharmaceuticals	++	+++
Advanced industries	Automotive	++	++
	Aerospace and defense	+	++
	Advanced electronics	+	++
	Semiconductors	+	++
Finance	Financial services	++	+++
Telecom, media, and technology	Telecom	+	++
	Media	+	+
Travel, transport, and logistics	Logistics	+	++
Insurance	Insurance	+	+



SUMMARY OF THE SOLUTION'S COMMERCIALIZATION POTENTIAL

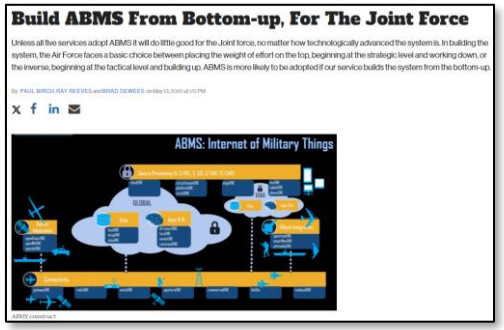
Starting with PACAF, commercialization will extend to ABMS users and the corp's supporting that techdev

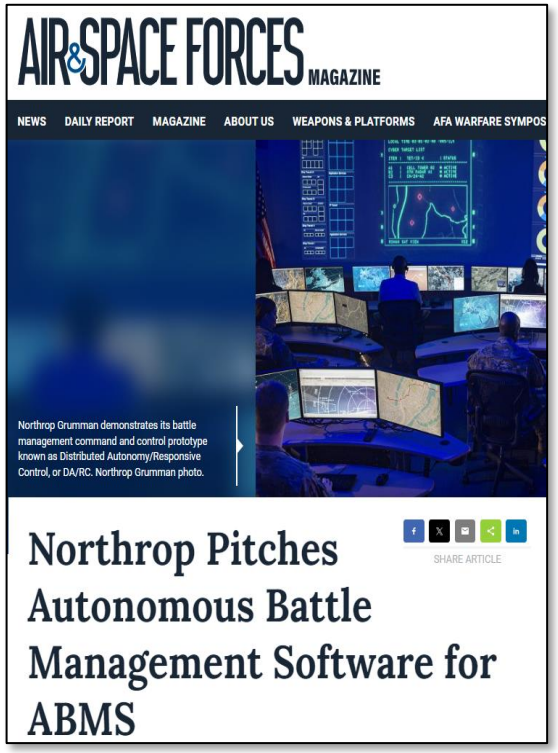
DOD WANTS THIS TECHNOLOGY



- PACAF is launch partner
- 613 AOC (Phase 1 End Users & Customers)
- Engaging with others (incl NIWC):

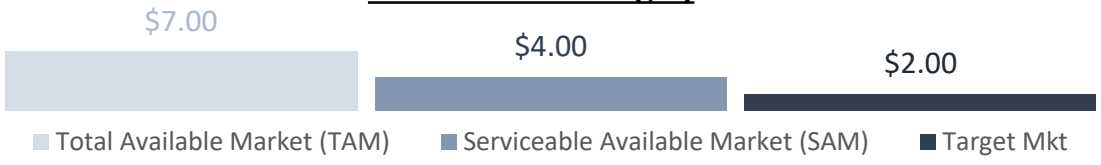
ABMS DEFENSE CORPORATIONS WANT THIS TECHNOLOGY





DOD MKT SIZES ($B)

CORP MKT SIZES ($B)



Key personnel represents one of the most experienced military quantum application teams in the world

- PI/Ethan Krimins leads QRS and has been PI on 3 DoD quantum projects. 7+ years of quantum coding on all major QC's. 20+ years of IT Project Commercialization leadership at GE. U. of Rochester (Math/BA/1991). Columbia U. (IT/MBA/1997). US Navy Veteran. Resume attached in Vol 5. Our PI will spend X% of his time (~8 hours per week) working on this Phase 1. Other responsibilities incl spending 30% of his time managing our P3 awarded with the Air Force in 4Q23 (contract No. FA810923CB003).
- Purdue University is the Research Institution. Professor Andy Jung has extensive quantum optimization design/development knowledge.
- Air Force Institute of Technology and AFRL are supporting. Details on next page.
- Atom Computing is subcontract. Mr. Greg Muhlner is Neutral-atom engineering expert liaison and commercialization co-lead (with Ethan).

Quantum Research Sciences LLC

Mr. Ethan Krimins (PI)
31 yrs experience tech pgm dev & 5 yrs in quantum computing
513-633-1604
ekrimins@quantumresearchsciences.com

PURDUE UNIVERSITY

Dr. Andy Jung (RI Lead)
Professor w/ 18 yrs experience in physics and quantum computing
765-494-5399
anjung@purdue.edu

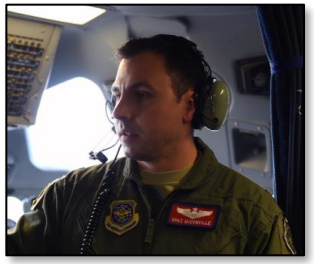
AFIT Air Force Institute of Technology

Dr. Larry Merkle

AFIT Air Force Institute of Technology

Dr. Lelia Hsia

AFIT Air Force Institute of Technology



Lt Col Sean McConville

AFRL and Air Force Institute of Technology details on next page

atom computing

Mr. Greg Muhlner
10 yrs experience in IT comercialization and Quantum Computing
202-437-9397
gmuhlner@atom-computing.com

USAF's top 2 quantum teams (AFIT & AFRL/RI) supporting this project (letters incl. in DSIP Volume 5)

Dr. Larry Merkle
Professor w/ 45 yrs experience in computational physics and 7 yrs in quantum computing. 937-656-5550
laurence.merkle.1@us.af.mil

Dr. Lelia Hsia
Major w/ 5 yrs experience in physics and quantum computing
937-656-5535
leleia.hsia.2@us.af.mil

Lt Col Sean McConville
Lt Col McConville is weapons school grad with extensive op system integration expertise
123-456-7890
email

AFIT
AIR FORCE INSTITUTE OF TECHNOLOGY

LOI

AFRL
THE AIR FORCE RESEARCH LABORATORY

DEPARTMENT OF THE AIR FORCE
AIR FORCE RESEARCH LABORATORY
INFORMATION DIRECTORATE ROME NY

26 February 2024

MEMORANDUM FOR USAF/AFRL STTR TEAM

FROM: AFRL/RI
525 Brooks Road
Rome New York 13441

SUBJECT: USAF X22D-OTCSO1 Phase I Letter of Support

References: (a) 15 U.S.C. §638
(b) U.S. Small Business Administration SBIR/STTR Policy Directive (May 2019)
(c) 5 C.F.R. §2635.702(c), Exception (1)

1. Purpose: The purpose of this memorandum is to document interest in working with Quantum Research Sciences (QRS), Air Force Institute of Technology (AFIT), Purdue University and Atom Computing on a quantum computing project being submitted for an Air Force STTR Phase I award under proposal FX24D-PTCSO1-0135.

2. Defense Mission Need: The quantum technology being proposed in this submission is aligned with the USAF strategic capability for Rapid Global Strike. Specifically, quantum computing can deliver a logistical optimization more accurately and rapidly than conventional classical computers. If successful, this technology would provide valuable friendly force optimization details for USAF operations.

3. Project Timeline: We expect this Phase I effort to be completed within the 3 months allocated.

4. Matching Funds: No matching funds are provided by AFRL/RI.

5. Phase II Support: If Phase I is successfully executed, we are interested in supporting the adoption of Phase II software into the Air Force.

6. Conclusion: We are committed to the success of this project and hope that AFRL/RI Quantum Team support will lead to selection of this proposal for award. Please feel free to contact the undersigned with questions or requests for clarification.

HAYDUK.MICHAEL.J.1228764856 Digitally signed by HAYDUK.MICHAEL.J.1228764856 Date: 2024.02.26 12:46:56 -05'00'
MICHAEL J. HAYDUK, PhD., DR-V, DAF
Deputy Director, Information Directorate

Air Battle Management System (ABMS) and Command, Control and Communication Battle Management (C3BM); PEO's delivering JADC2; this capability a priority for AF

USAF LETTER OF SUPPORT FOR THIS COLLABORATION (INCLUDED IN VOLUME 5):

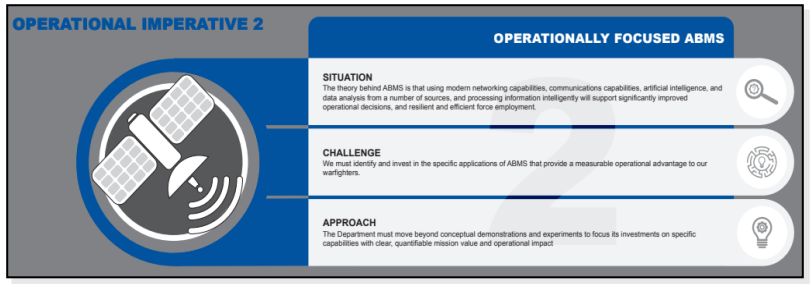
- PACAF →
- Col Vanoni, Deputy Director of Ops at AMC/DA3 →

THIS TECHCHECKS MANY AF BOXES:

☑ **Modernization Priority:** Quantum Sciences

☑ **OUSD (R&E) Critical Tech Area:** Quantum Science

☑ **Operational Imperative:** Operational Focused ABMS



☑ **Competency modeling**: Total Force Development

☑ **Strategic Capability:** Resilient Information Sharing

☑ **Core Mission**: Rapid Global Strike

Col Vanon

PACAF LOS

Immediate collaborative engagement with PACAF/613 AOC with customer discovery and passionate research will drive towards P2-ready technology program plan and system architecture

OBJECTIVES	WHAT WILL BE DONE	SUCCESS	Timing	R&D for Increasing Feasibility	Increase Commercialization Potential
PACAF Collaboration	Recurring weekly meetings	Customer Discovery	continuous	✓	✓
PACAF & other AF Input	Research w/End Users, Customers and other stakeholders	Process Chart	Month 1	✓	✓
Non-AF Input	Research w/End Users, Customers and other stakeholders	Process Chart	Month 1-2	✓	✓
Quantum Tech Design	Finetune quantum algorithm and layout integration	Software Architecture	Month 2	✓	
System Integration Design	Layout system integration (cloud, cyber, etc.)	System Architecture	Month 2-3	✓	
P2 Program Plan	End User, Cust & Stakeholder engagement	P2 MOU	Month 3		✓

Stakeholder collaboration, direction, & engagement to be built around these questions and other input:

PACAF Operations and quantum application integration:

- What compatibility challenges might occur when integrating quantum algorithms into existing ABMS (legacy software, data formats, etc.)?
- Are there anticipated difficulties in ensuring seamless communication between classical ABMS systems and quantum components?

Classical/Quantum Connectivity:

- How will classical and quantum components exchange info in an integrated system, especially during real-time decision-making scenarios?
- How will the integrated system handle feedback loops between classical and quantum processes?

Cyber Security:

- How do we protect sensitive data during both processing and transmission within the ABMS and quantum cycle?
- How will the quantum algorithm align with existing AF security policies and encryption processes?

Simulation and Testing:

- What test environments or simulation tools can be used to evaluate the quantum software effectiveness?
- How will we simulate realistic scenarios to ensure the quantum tech robustness in operational PACAF conditions?

Benchmarking and Validation:

- Are there predefined datasets that can be used to validate results obtained from the quantum algorithm against classical optimization methods?
- How will the criteria for success be identified (performance metrics, thresholds, etc.) and what benchmarks will be used?

Scaling Quantum Computing Resources:

- What is the scaling plan for the quantum computing resources as the complexity of asset optimization problems increases?

AF Commercialization, non-Def commercialization & P2 traction:

- What AF, other DoD, Defense Corporations and non-def/commercial companies will benefit from this tech and how do we impress them?
- Are we listening to what 613 AOC & PACAF are telling us and delivering substantial value to ‘Operationally Focused ABMS’?

Phase I priorities are customer discovery and tech designs.

Tasks	Duration	Description	Perf.
Kickoff meeting	Days 0-5	Coordination schedules and identify users, customers, stakeholders & leaders	All
Engagement & research	Days 6-14	Start obtaining input from stakeholders (see questions)	QRS
ID current state & future state processes	Days 15-21	Build out ABMS process chart to work into software and system architectures	AFIT
High-level quantum framework design	Days 22-28	Begin draft architectures in collaboration with team	QRS
Commercialization pre-work	Days 29-35	ID ABMS, JADC2, etc. stakeholders, non-AF users and Corp ABMS teams	QRS
AFIT critical review of framework	Days 36-42	Independent review (inclusion of AF & DoD needs, capabilities, etc.)	AFIT
Preliminary report (**DELIVERABLE**)	Days 43-49	To incl: draft architectures, U/I plan, end user/customer input	QRS
Obtain support for P2	Days 50-56	PEO engagement, integration of tech, MOU	QRS
Map out quantum hardware connectivity	Days 57-63	Detailed process for using Atom’s quantum computer	Atom
Simulation	Days 64-70	Detailed walk thru of future state, data/inputs, etc. and refine architecture	QRS
Ensure ABMS engagement	Days 71-78	Hard review that we are working towards is ABMS-feasible	QRS
Obtain MOU	Days 79-86	Obtain MOU’s from DAF/Com’l End Users/Cust’s	QRS
Final report (**DELIVERABLE**)	Days 87-90	To incl: process chart, software architecture, system architecture, P2 plans, …	QRS

We will drive engagement with ABMS and the PEO's delivering JADC2. Lessons learned from our prior AF quantum PI → P2 → P3 transition will benefit this effort.

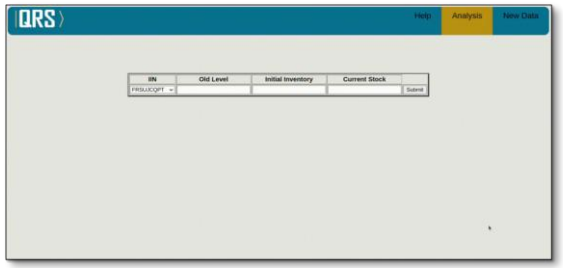
- ABMS is such a comprehensive initiative that this quantum application will need to focus tech engagement into one area:

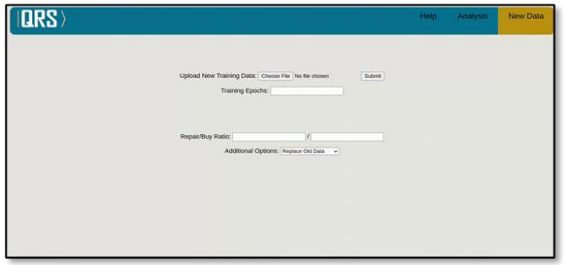
ABMS FOUR THRUST AREAS

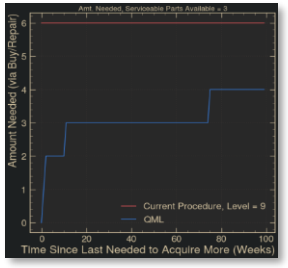
1. Architecture and Systems Engineering (common standards and technologies necessary to integrate programs into the DAF Battle Network)
2. C3BM Digital Infrastructure (programs that develop secure processing, connectivity, and data management)
3. C3BM Software and Applications (Could-Based Command and Control network (CBC2) to integrate air defense data to support homeland def)
4. C3BM Aerial Networking, Airborne Edge Node (enabling tactical aircraft to connect with command and control centers)

- Integration to C3BM via an existing system (vs. development of a new interface) may be easiest path

- Working quantum optimization software will be developed early in Phase II, and for that to happen, the 3-month (not a lot of time) P1 research/collaboration needs to be aggressive. Following are pics of our prior quantum contract's P2 deliverables; which although not pretty, proved to our AF stakeholders that the tech was functional and worthy of transition.



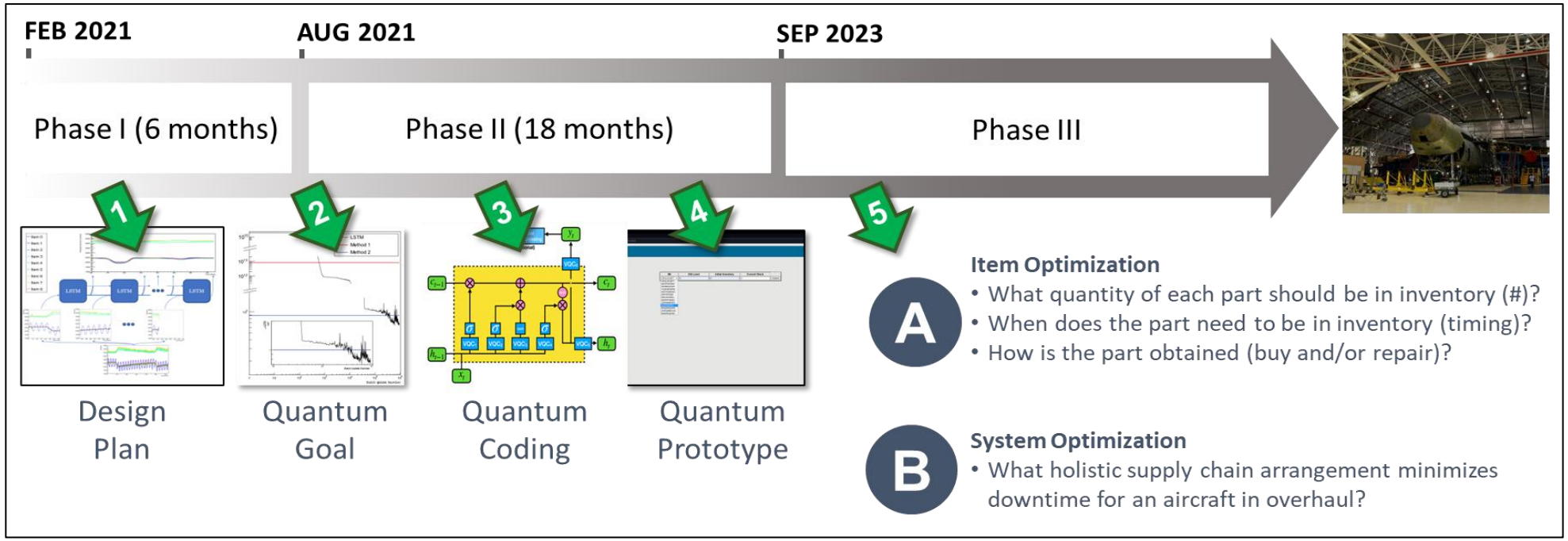




- Connectivity will be designed into the system architecture from the earliest point to minimize transition delays, with emphasis on IL-5/6 cybersecurity. In our current project, this was as time-consuming as the actual quantum coding.

QRS developed and operationalized the USAF first production-level quantum software

- This occurred via a prior USAF Open Topic (AF20C-TCS01) with Proposal Number FX20C-TCSO1-0452 (Supply Chain Inventory Forecasting on a Quantum Computer)

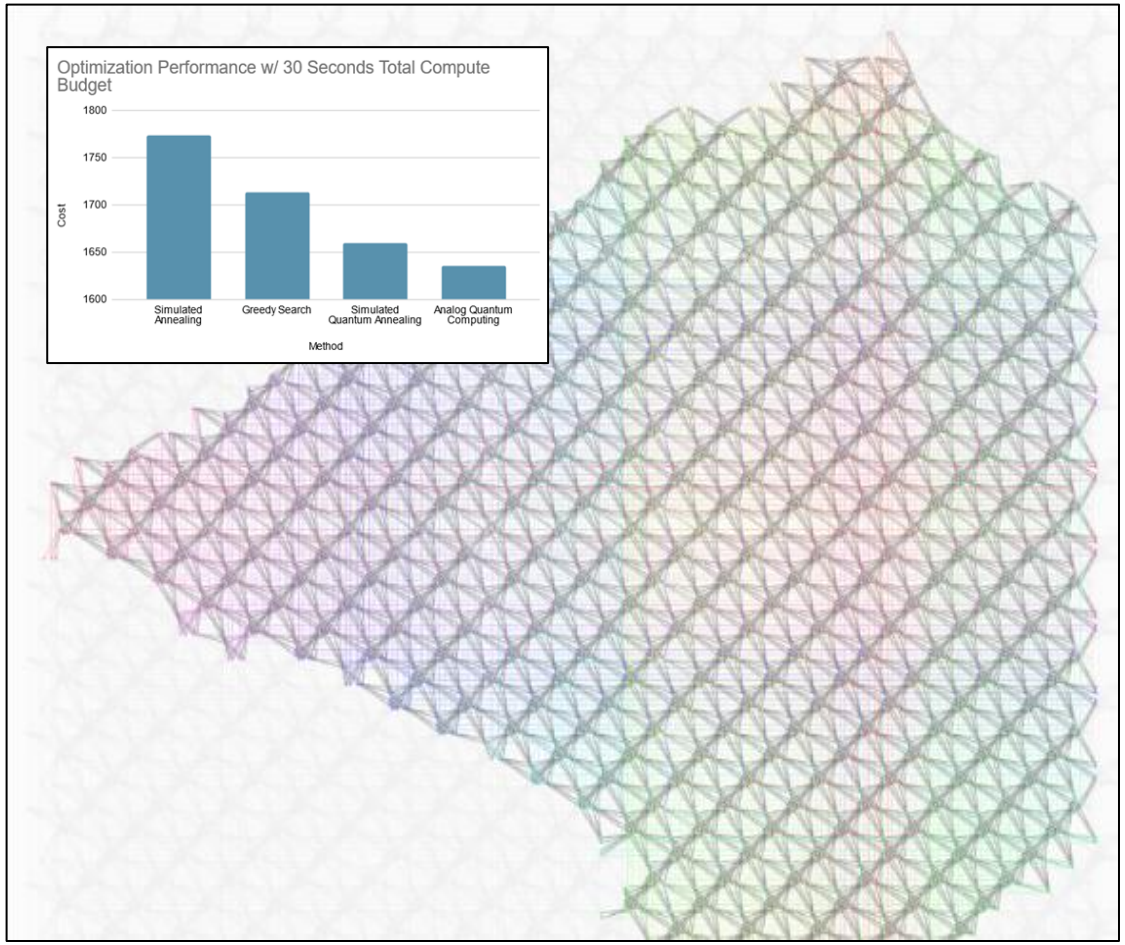


- That STTR transitioned through Phase I, Phase II and Phase III, between 2021 and 2024.

- USAF STTR Phase III quantum contract (FA810923CB003) is currently in place with 418 SCMG at Tinker AFB under AFMC. POC: Mr. Curtis Mears, curtis.mears@us.af.mil, telephone: Work Cell: (405) 820-4674. Comm: (405) 582-4700. DSN: 852-4700

Submission team has expertise in achieving world-record optimizations and integration to system technologies

- QRS has used quantum computing to solve optimization problems where exabytes of ambiguous, dynamic data needs to be quickly analyzed [1], and QRS boosted the run configuration performance of a quantum computer by 1000% [2].
- QRS employees are experienced with nearly all quantum machines (having worked on IonQ, DWave, Honeywell/Quantinuum, IBM, etc.) and know the pro/cons of each system. The graphic (top, right) is a world-class optimization we performed on DWave's QC showing 5600 interconnected hardware qubits and 170 logical qubits; benchmarking against classical algorithms (bottom, right).
- Atom Computing's team has expertise in neutral atom computing and has produced a large volume of publication related to optimization [3-6].



[1] Wildridge, A.J, et. al, (April 3, 2023). *Track clustering with a quantum annealer for primary vertex reconstruction at hadron colliders* [arxiv.org/abs/1903.08879]
[2] Wildridge, A.J., et. al., (July 12, 2021). *Reconstructing proton-proton collision positions at the Large Hadron Collider with a D-Wave Quantum Computer*, DPF2021, https://indico.cern.ch/event/1034469/contributions/4432259/attachments/2281345/3876267/APS%20DPF%20Summer%202021.pdf
[3] King, J. (2023). Mid-circuit qubit measurement and rearrangement in a Yb atomic array.
[4] King, J. (2023). Scalable neutral atom-based quantum computing.
[5] Pudenz, K. (2024). Iterative assembly of 171Yb atom arrays in cavity-enhanced optical lattices
[6] Pudenz, K. (2017). Quantum Annealing and the Satisfiability Problem .

QRS has AF security clearances and access (CAC Card, Desktop Anywhere, .ctr@us.af.mil emails, etc.)

- UEI #: GHZFXJ9MEVJ1
- CAGE CODE #: 9CEN4
- SBA Control ID #: SBC_002499325

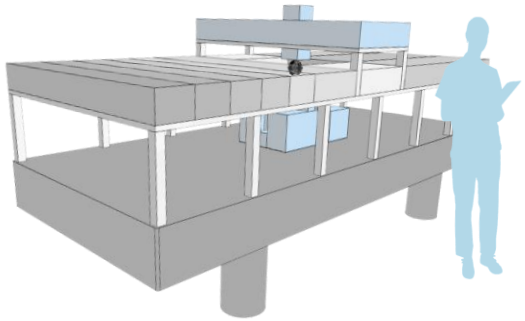
- QRS will exercise management direction and control of the performance of the STTR.
- QRS has secure computing inside our office at Purdue University
- QRS systems with the USAF are IL5 compliant
- System Security Plan (SSP), Incident-Handling Capability Plan (IHCP) along with Software QA documentation is on file with the USAF

- SBC Name: Quantum Research Sciences, LLC ← please note: this is novation from FlightProfiler
- SBC Address: 130 North 3rd Street, Lafayette, Indiana 47901, United States
- SBC Website: www.quantumresearchsciences.com
- SBC Category: Veteran owned business

Atom Computing is providing access to one of the most advanced computers ever created; which will be a new and powerful resource for ABMS

OTHER RESOURCES:

- If IL5 or higher level work is required, QRS works on a secure endpoint that includes MS GCC access within the Purdue ecosystem at a secure location (the same currently being used for the USAF).
- AFIT is at WPAFB and has access to AF facilities.
- AFRL/RI has access to numerous quantum assets (including IonQ and IBM quantum computers) as well as a team of quantum science experts.



Atom's Neutral Atom Quantum Computer