Quantum Radar: Design Documentation

Riley Ashok, Matthew Montana, Michelle Pishchik, Zachary Phillips

Abstract

Our goal is to create a stationary, defensive radar capable of detecting stealth aircraft without relying on returning signals by harnessing quantum principles of superposition, interference, and measurement. Our system will work between a Low Earth Orbit (LEO) satellite constellation and a ground station on Earth. Using a variety of systems modeled after Mach-Zehnder Interferometers, the radar will be able to tell the velocity, size, and location of any object in the beam, including any aircraft using stealth technology. High energy, single pulse lasers will send pulse signals through a beam splitter on the satellite, where mirrors will then direct the light into a variety of shapes before arriving at the ground station. Mirrors at the ground station will then redirect the light into a second beam splitter where the two paths will recombine. Photons detected in Detector 1 will be regarded as either no object in beam or no information gained. Photons detected in Detector 2 will be regarded as an object in the path. Individual beams will correspond to pixel outputs on a computer graphic display and information learned about the velocity or shape of the plane will be combined with the many other individual systems to create a working image of the aircraft.

Improvement Factors:

Function

Our design is simpler than other existing quantum radars in the field, such as two-mode squeezed radar or quantum illumination radar, particularly due to the fact that it does not use entanglement. However, due to its extensive use of quantum physics and its susceptibility to error, it is very hard to implement. Its use of specialized equipment impedes many simple implementation methods and the implementation of the device will have to account for a lot of natural phenomena. However, after implementation, the operation of the device is not overly complex. It will have to be continuously maintained, particularly that the mirrors will have to be kept clear, but most of the day to day running of the radar will be computerized and easy to keep in operation.

Aesthetics

The visual appeal of our solution is not very important, however, a balance of high-tech and old school methods will help it to be sold in the military and to congress. The high-tech will appeal to the new caucuses calling for overhauls and updates within the military, and the rise of new generation technology. However, an older element will help it to settle among the older members of congress and military leadership, as it will make it feel more reliable and less alienating when compared with the older military technology.

Ergonomics

The radar would be incredibly hard for humans to use alone, and would likely have to rely heavily on the use of computers. However, the actual computer interface is incredibly easy for humans to use. Each single system that the radar is made out of will correspond to pixels and graphics on the output, and computer systems running the math of the system will allow people to easily get an idea of what the plane looks like and where it is.

Safety and Ethics

The radar is very safe to use. Because it uses light, there are very minimal risks, as it is a level of radiation that we are exposed to regularly everyday. The frequency 1550 nm is also regularly used in military LiDAR today as well, and should not pose any significant threat to human health.

Standardization

Both the laser and satellite would likely have to be custom. Due to the large distance between the earth and a geostationary satellite, the beam waist radius would have to be incredibly large. While they are makeable, they are not available for commercial sale or use, and would have to be custom ordered. Similarly, the satellite would likely have to be specially designed to hold and operate the radar. The ground base would also have to be specially built for the radar, such that it has the capacity to reflect and receive the signals. However, many other parts of the radar can be created using standard parts. Beam splitters, mirrors, and detectors can all be ordered using standard, current models. Detectors may not be available for commercial sale at the precision necessary, but they are currently being made.

Quality Control

One component that will be very hard to implement or produce is the laser itself. Because of its incredibly large beam waist radius and the absolute necessity that it produces single pulses at a time, it could be very hard to produce. In all parts of the satellite, margins of error must be as low as possible in order for it to work, making it very hard to manufacture. Unfortunately, there is very little room to alter the design, as the states and scale that we are working with are incredibly fragile, and need very specific conditions to work. The hardest part will be ensuring that the beam distances are exactly the same, so that the photon combines correctly in the second beam splitter. Using an incredibly precise laser should also help to ensure that only one photon is going through the system at a time.

Ease of Maintenance

The innovation would take a lot of time and effort to maintain, particularly due to the fact that the mirrors must be kept in pristine condition in order to correctly reflect the light and the path to the mirror from above must be kept clear. This means that if any debris or rain got on the mirrors, it would have to be cleared. The solution could be improved so that there was some sort of cover or self cleaning mechanism, or some way for the mirror to recognize that it would need to be cleaned. Additionally, the design would require a lot of power and possibly a lot of maintenance of the satellite to make sure the laser is always in working order.

Durability

The radar itself should be fairly durable. The weakest points will be the mirrors and making sure that they are kept in perfect condition and reflecting at the correct angle. The other weakest point will be ensuring that the two beam distances are exactly the same. If they are even slightly off, it could cause significant error. With high quality lasers and detectors, the main parts of the radar should be able to survive for a long time.

Environment

Our radar should not have any negative effect on the environment. The wavelength we have chosen to use is not harmful, and is often experienced due to the sun anyway. There should be no harmfully radioactive elements to the radar. However, there will be some intrusion to the environment as the ground station will have to be built and maintained.

Cost Estimation

Many of the parts of the radar will have to be highly specialized and highly precise with the lowest possible error. There are lasers, detectors, beam splitters, and mirrors that exist to these specifications, although they may not be available for commercial use. There is the possibility we will need a custom laser, however, we should be able to fit already existing lasers in. We would have to launch our own satellites or outfit existing ones with highly specialized equipment. Overall, the cost of implementation could be incredibly high, with a budget possibly around $7.5 million to $1 billion. Unfortunately, there is no real way to change the design to simplify manufacturing or use different materials due to the highly precise nature of the radar.

Feedback

We met with several experts in the field of Quantum Mechanics and Technologies, who were able to give us valuable feedback on our project.

Dr. Jeffrey Shapiro

No kind of quantum radar is currently in use. While there are some potential applications where they are useful, they are mostly in the lab.

Problems with our set-up:

- If there is any slight variation or time dependent differential path length, we will get an indication that something is present when it might not.
- Atmospheric turbulence: is occasiated with really small temp variations in air that change the index in fact in a minute that range from size and moving and evolving.
- Dashed lines will spread out and the waves will be large.
- Down at a single photon -> Ours is a quantum radar!

Ways to work around the problems:

- How high we want to choose the satellite to be
- How big the optics are
- If you take the products of the area of the receiver and wavelength and path length (add more math), you can form an image of the object
- You can find atmospheric effects and light you are sending out
- Be greater than one to get a single photons in the atmosphere

How can weather affect it

- Light with changing weather-> issue with coherence
- BUT amount of light is getting through varies
- You do want a beam
- Single photon system might not be working

Different Wavelengths:

- AVOID Absorption lines
- Differential absorption LiDAR
- Scattering gets worse with shorter wavelengths
- Blue is preferentially scared then longer wavelengths
- Probably want it at a shorter wavelength

Set up:

- Computer could work
- Turbulence: Computer Simulation is very computation defensive

What would not work:

- Start as a sequence of single photos and vacuum propagations
- Differentiation calculation to get to another end
- Well what happens when something is the phase of the wave changes
- How much phase gives you what kinds at the under end
- Probabilistic
- Filtering (background light)
- Diffraction efficiently
- Background light
- Phase shift
- Differential attenuation

No way to tell where is the beam the obstruction was, how to find plane altitude:

- Disturbed the propagation of light
- Literature of electromagnetic cloaking

Would it be a problem if there were overlapping sets of beams:

- No, as long as the wavelengths are different and they would just go right through each other

How would squeeze states be realistic and a benefit:

- Quantum radar that has been predicted theoretically uses quantum illumination
- Entanglement -> Correlation but quantum and stronger

Problems with this kinds of radar but it mainly uses a different system

- Uses linear algebra and calculus

How to use a physical number that was detected in detector 2

- 20 meters might be too small as some planes are bigger than that
- Think about pulses
- Probability is hitting each detectors and the pulses
- Probability Theorem (trials)
- Consider a receive operating characteristics
- Plan is not stations so each pulse is seeing a different amount of absorption

Maybe consider a smaller path, maybe drones?
Low earth orbit satellite or a geosynchronous:

- It would be better to have a stationary satellite that has lot of space between
- Trouble, very sensitive to phase and the two arms

What room for error for getting them out of shift or havigng a slightly longer beem distance?

- Stable to the fraction of a wavelength, very difficult.

Best detectors to use:
- Superconducting nanowirse single photon detectors: Fast with count rates in the millions

What type of laser should be used for this?
- Nothing really any good commercially avialiabele
- Laser -> not sending a photon
- Two photons into the detector-> changes things
- Laser light

Best ways to account for error?

Major sources:
- Background light -> need to filter the narrow pulse in time
- A specific wavelength in retrospect for turbulence

Dr. Wenchao Ge

Best tools for computer modeling our radar:
- (Brookhaven) - Quantum Prostrometry - using interferometric techniques to study the sky (photons coming to you from stars, learning things not accessible from classical telescopes)
- Relay Bound - fundamental resolution
    - Quantum Interferometry has

Stealth Aircraft gives a very short beam path deviation (harder to detect time differences)
- Astronomical objects give larger beam path distances

Key Question - How does noise provide fundamental limits?

50/50 Beam Splitters “should be fine” for our goals.
- Quantum Optics is a geometry problem
- Able the beam towards the correct way, different beam splitter won't work

Universality - if you have access to a certain universal quantum gate set, you don't need a specific beam splitter.

Quantum optics is usually pretty easily modeled by a classical computer, this isn't too complicated for a classical computer.

Photons come from the star, it comes from a beam and there's an object in the way

You can use different states of entanglement to find different parameters.

Ideal scale: quite large in order for things to work (gravitational pull is very weak).

What to look into: gravitational lensing and how astrometry are connected.

Dr. Michael Dascal

- Quantum is non-signaling, there is nothing you can do to determine if someone has done something to the other end of the entanglement pair (violates relativity)
- Current Quantum radars rely on reflection, rely on BEING reflected
- Different pairs emitted at different angles (or frequency?) can let you get the shape (you'd need an array of detectors) Detect angular range.
- Non 50/50 beam splitters could enhance detection on the lefts and rights, but if you want general scanning, 50/50 best (take with a grain of salt)
- Embedded/nested interferometers? (might not help, scan through)
- Sets of mirrors around a circle or a diamond (triangulate object, multiple data sets)
- You cannot tell where along the path the obstruction is
- Reducing error - spread of different energy levels
- Farraday estimates and identifying parameters and absorption probabilities
- Reflection v absorption probabilities (maybe not)
- Classical Computing is the way to go
- Separate Pyramids / nested interferometers

Dr. Shimon Kolkowitz

<u>We have been researching current designs of Quantum Radar, but we have had trouble finding a lot of specifics on how the current ones work. Could you please explain a bit about how they work and what other kinds of Quantum radar are currently in use?</u>

I'm attaching a review paper I just found online that does a decent job of describing the current state of the art. You can find specifics about the different designs/experiments in there, as well as in all the papers that are cited in this review.
Please note that quantum radar and quantum LIDAR are basically the same thing, the only difference is the frequency/wavelength of the radiation used (radio frequency for radar, roughly optical or infrared light for LIDAR.) It's currently generally easier to generate entangled photons in the optical part of the spectrum, so you might have more luck looking for quantum LIDAR experiments. In both cases the term is somewhat vague, and refers to the use of "non-classical"

(synonymous with “entangled,” or “quantum") states of electromagnetic radiation to enhance the sensitivity or performance of a sensor that is trying to use that radiation to detect/map out objects. There are a few potential advantages of using quantum states of light:

1. You can gain more sensitivity or spatial resolution for the same number of photons/amount of radiation
2. You can design your sensor in a way that the signals you detect are harder to “spoof" or “cloak" than with the classical versions of radar/LIDAR
3. Because you can enhance your sensitivity for the same number of photons, you can in principle use it to detect objects while making it harder for anyone else to know you’re looking

What are some current struggles in the field of Quantum Radar?
The biggest challenge is that it’s pretty hard to generate non-classical states of electromagnetic radiation, and if you do they tend to be sensitive to things like photon loss, which occur naturally when you send radiation out and then try to detect it when it bounces back. In addition, in general these approaches really only help when you’re working with very low light levels (see the points above) and that makes it very hard to achieve the necessary signal to noise ratios to be useful, or to compete with classical radar and LIDAR using much higher intensities of radiation.

What are some of the current applications of Quantum Radar?
To my knowledge there really aren’t any. This is a nascent quantum technology that doesn’t really exist in the real world yet. Potential applications would probably mostly be focused on national defense, since the main advantages are that you can potentially detect objects without an adversary knowing, and/or you can be confident that an adversary isn’t tricking you into thinking an object is there when it isn’t, or isn’t there when it is. However, there are very related concepts within the broader field of "quantum imaging” or “quantum illumination” with potential applications to biology and medicine, where you want to image inside of cells or living organisms, and using light that is too intense will damage the organism.

Equipment and Calculations:

Beam Splitters

We will use normal 50/50 beam splitters. As of current designs, they can be a normal size within a range of 5 mm to 2 inch cubes.

Lasers

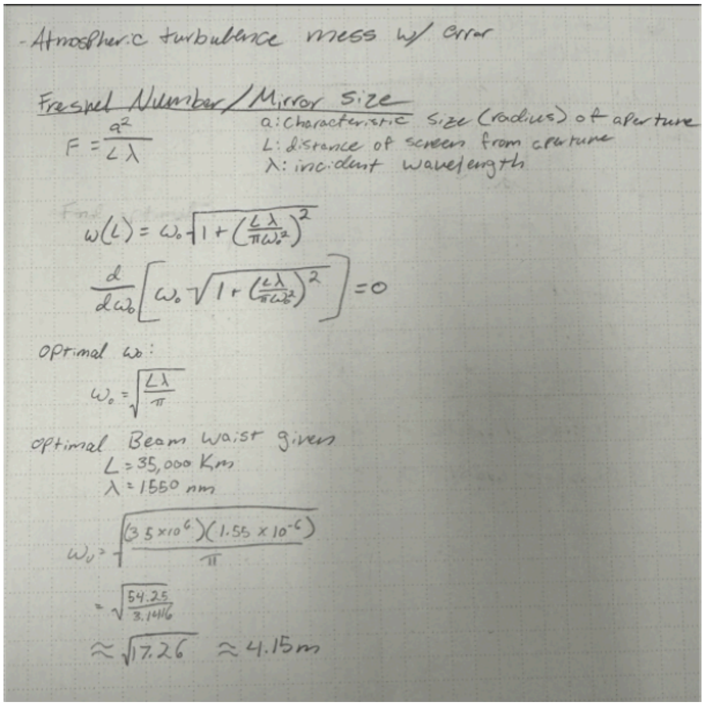
We want to use a single photon pulse laser using a wavelength of 1550 nm and beam waist radius of 31.4 mm.

Mirrors

- Sheet mirrors, highly polished, minimal imperfections

Optimal mirror size

- Due to the high distance between the satellite and the bottom station and the wave-particle duality of the photons, they will spread out significantly between the output and detection. Therefore, we must find both the optimal beam waist radius in the satellite and the minimum size the mirror must be to reflect all of the photons to the detectors.



- Atmospheric turbulence mess w/ error

Fresnel Number/Mirror size

$F = \frac{a^2}{L\lambda}$

a: Characteristic size (radius) of aperture
L: distance of screen from aperture
λ: incident wavelength

$$w(L) = \omega_0\sqrt{1+\left(\frac{L\lambda}{\pi\omega_0^2}\right)^2}$$

$$\frac{d}{d\omega_0}\left[\omega_0\sqrt{1+\left(\frac{L\lambda}{\pi\omega_0^2}\right)^2}\right] = 0$$

optimal ω_0:

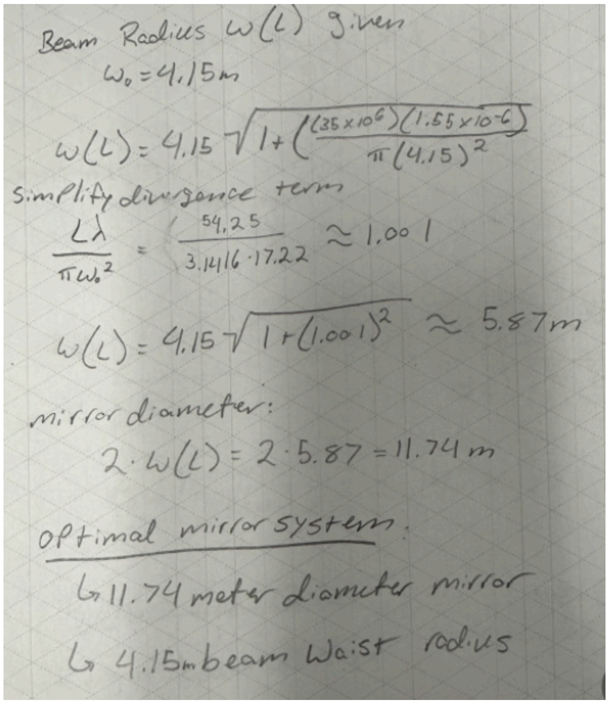
$$\omega_0 = \sqrt{\frac{L\lambda}{\pi}}$$

optimal Beam Waist given
$L = 35{,}000$ Km
$\lambda = 1550$ nm

$$\omega_0 = \sqrt{\frac{(35\times10^6)(1.55\times10^{-6})}{\pi}}$$

$$= \sqrt{\frac{54.25}{3.1416}}$$

$$\approx \sqrt{17.26} \approx 4.15m$$



Beam Radius $w(L)$ given
$\omega_0 = 4.15m$

$$w(L) = 4.15\sqrt{1+\left(\frac{(35\times10^6)(1.55\times10^{-6})}{\pi(4.15)^2}\right.}$$

Simplify divergence term

$$\frac{L\lambda}{\pi\omega_0^2} = \frac{54.25}{3.1416\cdot17.22} \approx 1.001$$

$$w(L) = 4.15\sqrt{1+(1.001)^2} \approx 5.87m$$

mirror diameter:

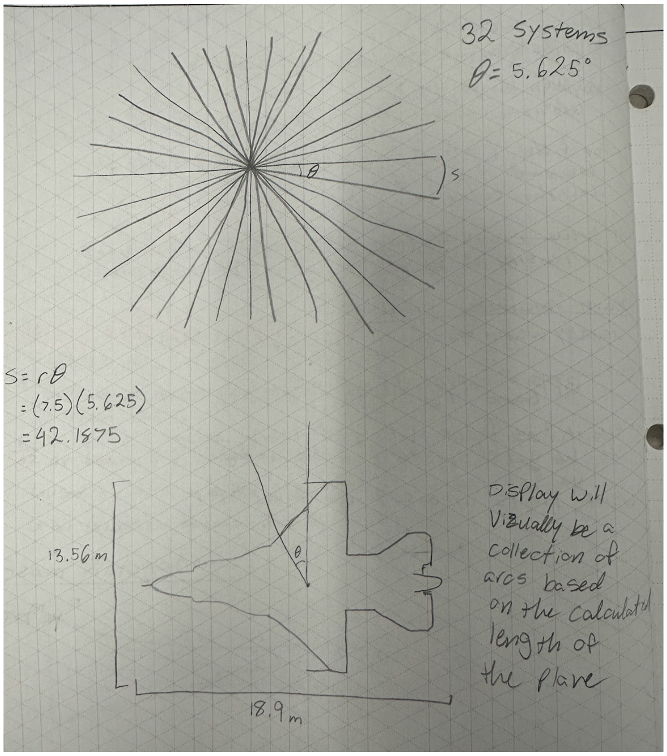
$$2\cdot w(L) = 2\cdot5.87 = 11.74\,m$$

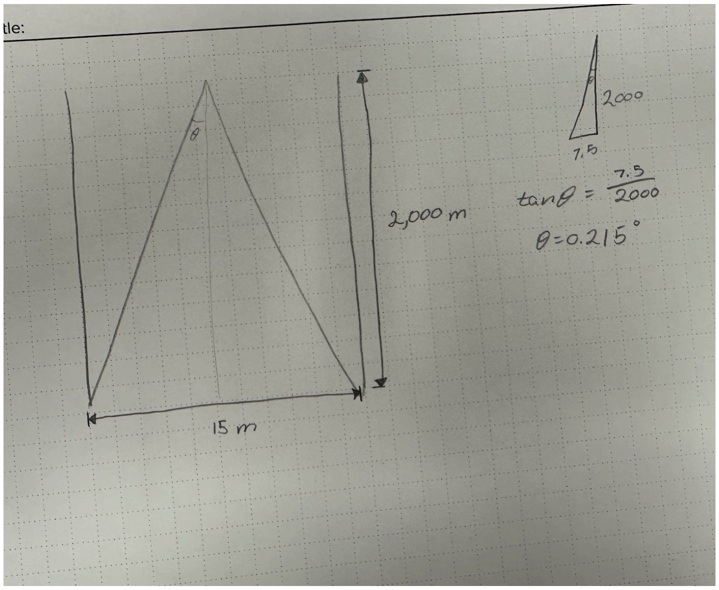
Optimal mirror system:

↳ 11.74 meter diameter mirror

↳ 4.15m beam Waist radius

Number of Systems





We will mount 32 individual systems in a cylindrical shape to create a display based on the radius between systems (5.625°) multiplied by the found length of the plane at that system.

<u>Detectors</u>

We have chosen to use superconducting nanowire single-photon detector (SNSPD or SSPD) for their "very high detection efficiency, very low dark count rate and very low timing jitter." They are able to detect single photons, which is critical for our device and are the fastest detector for single photon counting. They are very often used in quantum optical systems.

Math

Solving for the length of the plane in one direction and for the velocity.

$$l = (\frac{t_s}{t_r} + 1)d$$

l: Length of the plane

$$v = \frac{d}{t_r}$$

t_s: time silent (no signal at all detected)

t_r: time right (time from start of signal detection in D_2 to

t_s

d: distance between the beams

Computer Backend

Calculating the velocity and length of the plane:

```
import math
import scipy.constants as const

#define variables for find_time_and_velocity
planeLength = 0.0
beamDistance = 20.0
timeSilent = 0.0
timeRight = 0.0

planeVelocity = 0.0

parenthesis1 = 0.0
parenthesis2 = 0.0

def find_length(timeSilent, timeRight):
   parenthesis1 = timeSilent/timeRight
   parenthesis2 = parenthesis1 + 1
   planeLength = parenthesis2 * beamDistance

   print(f"The length of the plane is: {planeLength} meters")

   return planeLength

def find_velocity(timeRight):
   planeVelocity = beamDistance / timeRight

   print(f"The velocity of the plane is: {planeVelocity} m/s")
   print(f"----------------------------------")
   print(f" ")

   return planeVelocity
```

```
# this is the main code that validates the input and calls the find plane function
# do any output processing here and other global error handling
try:
   #inputs for find_length_and_velocity
   timeSilent = float(input("Enter the TimeSilent: "))
   timeRight = float(input("Enter the Time Right: "))
   print(f"-")


   # Calculate the function
   length = find_length(timeSilent, timeRight)
   planeVelocity = find_velocity(timeRight)
```