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STRATEGIC IMPLICATIONS OF FREQUENCY COMBS:

CROSS-BAND SYNTHETIC APERTURE ELECTRONIC WARFARE

by

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DISCLAIMER

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Biography

Col (sel) Brian Mork, Ph.D., is an Air Force Reserve Individual Mobilization Augmentee assigned to the Air Force Technical Applications Center (AFTAC), attending Air War College on a school duty tour. In his civilian capacity, he is employed as an instructor at the Air Force Test Pilot School, Edwards Air Force Base, California.

After obtaining a doctorate degree in Analytical Chemistry at the University of Illinois, Lt Col Mork spent 11 years as an active duty pilot, flying KC-135s under Strategic Air Command (SAC), Military Airlift Command (MAC), and Air Mobility Command (AMC), and participated in the last nuclear alert taxi exercise of our nation before the Berlin Wall fell. He graduated from the Air Force Space Command's Space Tactics School (STS) and while on faculty at the United States Air Force Academy (USAF), he instructed in TG-7s and was the Communications, Data, and Telemetry faculty lead for Falcon Gold, the Academy's first satellite. He transitioned to the Air Force Reserves, flying with the 63 Air Refueling Squadron (ARS) at Selfridge Air National Guard Base and during this time was invited to interview for a National Aeronautics and Space Administration (NASA) astronaut position. He spent 9 years teaching at Test Pilot School before transferring to AFTAC and is now doing technical acquisitions work in the field of nuclear forensics. As a civilian, he served as a Supervisory Control and Data Acquisition (SCADA) programmer in the automotive industry, an Operations Engineer for the Airborne Laser, a 412th Test Wing Electronic Warfare Directed Energy Subject Matter Expert, and Assistant Professor of Chemistry, before transferring to a full-time civilian government job instruction at the USAF Test Pilot School.

Abstract

This paper describes technology that is exotic today yet will be commonplace in 2040. Frequency combs exhibit time-domain precision approximately eight orders of magnitude better than other contemporary options. This allows creation of dynamically changeable synthetic apertures (antennas or lenses) which give precision, power, and sensitivities orders of magnitude better than contemporary systems. Rather than using a single aperture with a single frequency such as visible light, infrared radiation, ultraviolet, terahertz radiation, radio frequency or audio, cross-phenomenological transmitters and receivers use one frequency at potentially multiple sources and a different frequency at the target.

This discontinuous step in capability has operational implications which suggest different strategies to engage adversaries. Frequency combs emphasize Air Force decentralized execution, centralized control, and concentration of power. They provide defensive advantages of security, obscurity, and protection of our intent in the face of ubiquitous intelligence collection in the year 2040. Offensive advantages include inherent clandestine characteristics, resistance to denial and deception, and incredible sensor resolution and aspect angles using arbitrarily large synthetic apertures. These techniques allow electronic warfare operation in contested environments, long distance access, and tunneling access into enemy airspace. These methods are usable on the battlefield of 2040, when adversaries will have extensive intelligence collection capability.

I. Introduction

In Ecclesiastes 1:9, Solomon says, "What has been will be again, what has been done will be done again, there is nothing new under the sun." That may be true of people's character and the way humans engage in conflict, but advances in technology cause the nature of conflict to change. For example, America's free access to areas of conflict can no longer be assured, thereby forcing operational plans to be rewritten to consider Area Access and Area denial (A2AD). Additionally, by 2040, the world will be awash in data, creating translucent awareness for those that understand how to process the volume and turn data into knowledge.[1] This paper makes a case that, in this environment, leveraging cross-band electronic warfare techniques will allow America to have weapons effects at a distance and collect sensor information with impunity.

Imagine enemy fighters scrambled to intercept American aircraft or ships patrolling near disputed territory. Anytime an enemy fighter aircraft comes within 10 km of American assets, the pilot starts to experience unexplained flight control instabilities and communication problems.

In another imaginary scenario, an adversary might use fuel pipeline distribution to establish energy hegemony over the region, thereby influencing American allies to make new relationships. If the pipeline project were to experience failures at pump stations and be unable to meet safety requirements, perhaps the customer would instead import renewable hi-tech solutions from America.

These scenarios are possible outcomes using new Frequency Comb (FC) technology. Experienced researchers describe FC as "…simple and compact tools that phase coherently connect the radio frequency domain (below say 100 GHz) with the optical domain (above say

200 THz)."[2,3] A garden-variety physicist or engineer might say FC techniques measure and control aliasing across many decades of frequency, measuring beat frequencies between optical carriers. To the layman, FC is a way of converting between light and electricity while generating exceptionally precise time signals and generating (or measuring) signals anywhere in between.

FC offers time synchronization many orders of magnitude better than GPS, allowing frangible, dispersed, cooperative engineering designs previously impossible. FC is used for high-resolution pulse spectroscopy, astronomical research including Einstein relativity corrections, generation of hard UV light, quantum electrodynamics research (QED), primary time standards distribution, optical time transfer over 1000 km ranges, and white light (continuous spectrum) lasers.[4] An "…optical frequency comb allows one to synthesize almost any optical frequency."[5] Since 2008, methods have extended capability down to the radio spectrum, and further work may allow generation of acoustic signals using laser interferometry.

Applying these capabilities to military concerns, FC addresses at least six Potential Capability Areas (PCAs) published by the Chief Scientist of the Air Force in the period 2010-2030:[6] Frequency-Agile Spectrum Utilization; Dominant Spectrum Warfare Operations;[*] Precision Navigation/Timing in GPS-Denied Environments;[*] Next-Generation High-Bandwidth Secure Communications; Fractionated, Survivable, Remotely Pilot Systems;[*] and Fractionated and Distributed Space Systems. No new major weapons platform is required, consistent with a fiscal environment that deters new major platforms compared to mission system upgrades and incremental capability improvements. The Chief Scientist of the Air Force writes that, "The challenges the Air Force faces require S&T to place increasing emphasis on capability-based efforts over platform-centric efforts."[7] While the cost of new aircraft is hotly debated in budget

[*]Ranked by the Chief Scientist of the Air Force as "Highest Priority."

circles, FC slips under the financial radar for unit cost and rides on any soldier, vehicle, ship, or aircraft.

The capability of FC dovetails well into the technology roadmap laid out by the Air Force. In particular, there is a significant match between FC and five technology themes the Chief Scientist expects to develop between now and 2030:[8]

- **Platforms will yield to capabilities**. FC optical emitters and receivers can be put on new platforms or retrofit to existing platforms.
- **Manned will become remotely piloted**. Aggregated FC arrays can use an unlimited number of platforms, allowing creative synergetic use of unmanned vehicles, satellites, or ground stations.
- **Fixed designs yield to agile designs**. Dynamic arrays can reconfigure on the fly to create desired resolution and signal strength. Frequency of electronic warfare effects will be tunable from low-band RF (perhaps acoustic by 2040) to visible light.
- **Integrated systems yield to fractionated designs**. FC arrays can be aggregated or separated based on resolution needed, survivability, and power concerns.
- **Strike missions yield to dissuasion**. Electronic Attack on adversary systems takes away their confidence to use their equipment. For example, because Chinese engagement paradigms are based on analytical predictions of tactical engagement outcomes, we may forestall hostilities by preparing the battlefield in peacetime using FC.

Beyond *having* assets with technical advantage, the power in a 21st century war will be controlling knowledge of how the other side is *using* assets. When adversaries have on-par sensing capability, obscuring our intent is important. For example, FC optical emitters on a fleet of UAVs may appear to provide capability to blind EO sensors, while they are really capable of a subsumptive[9] goal to create a large synthetic aperture capable of focusing RF energy on specific radar sites or sensing millimeter size target areas or fingerprinting targets for identification. Intelligence images and count of assets will be less important than discerning intent with assets. Discerning intent is much more expensive in the currency of intelligence, and will be critical to hide to retain advantage in future battles. FC's physical characteristics inherently disguise our intent, while FC capability provides an opportunity to learn theirs.

II. Understanding the Future

The Center for Strategy and Technology at Air War College can provide an unabridged version of this paper discussing how the world of 2035-2040 will be different. *In summary, the character of future battles will be target discovery, tracking, identification, and fast handling of large data sets leading through the chain of sensor to a shooter – and this is what FC excels at.*

III. Problems that FC Can Solve

After 67 years of Air Force innovation, the battlefield still has several challenges that FC can uniquely address. After documenting some of the problems, the technology of FC will be described in more detail, before presenting two sections outlining FC attack and sensing capabilities that can help.

Through the 1990s, the Revolution in Military Affairs (RMA) was heralded as a military end-all, embodied in the development of precision weapons (the material part) and campaigns of shock and awe (the process part).[10] However, the Achilles heel of precision weapons – precisely hitting the wrong target – can cause huge blow-back, ironically with a different type of shock and awe that no diplomat wants to deal with. A previous chief of counterintelligence for the director of National Intelligence succinctly say, "Precision is useless without intelligence."[11] Think of the accidental bombing of the Chinese embassy in Yugoslavia during Operation Allied Force in 1999, which is a manifestation of the data/information problem discussed earlier.

RMA has gotten a bad name because it works against only the middle ground technical adversary. RMA has shown a weakness of dealing with enemy extremes – on the high end, the adversary that is a technical peer capable of denying traditional air superiority, and on the low end, the non-state non-technical adversaries that have no airspace to control. FC technology augments prior RMA because it answers the high- and low-end adversaries.

We are limited by technical peers who can do area denial or deny access.[12] To address peers, FC electronic warfare attack allows us to reach in from a distance and cause effects much more subtle, covert, and finessed than jamming of radars. These techniques allow us to cause technical mayhem with the enemy, denying or spoofing signals ranging in frequency across many bands: audio, VLF, VHF, UHF, Microwave, Terahertz, IR, visible, and ultraviolet. America should consolidate operational and strategic implications of FC while adversaries are still adopting the technology.[13] This will keep us one step ahead of advanced adversaries as we enjoy a technological wedge of time.

America is also challenged by insurgent and terrorist hit and run engagement styles, especially when mixed among an indigenous populous. Identifying and tracking the bad guys separate from the innocent civilians becomes the challenge. To address this problem, FC remote sensing allows identification of assets (materials, people, effluents, vehicles) allowing social link analysis or tracking of king-pin personnel. This can be done without over-flight or territorial violation that is difficult to explain on the world stage. FC is a tool for "…the airpower community to focus more resources and education on the conceptual development of coercive strategies and conflicts in the lower end of the intensity spectrum."[14]

Beyond operational concerns of addressing enemies at the extremes, laws of physics also support a move toward FC. RF cannot be narrowly aimed and loses power rapidly over distance.

The beam width or energy spread of an emitter (and the listening footprint of a sensor) is inversely proportional to the ratio of antenna size divided by wavelength. In other words, fine control and fewer side lobes are possible with big antennas and small wavelengths.

Because airborne antennas are typically only ~30x larger than the wavelengths of use, beam spread is wide (~30 degrees rule of thumb) and there are multiple side lobes.[†] With broad beams and uncontrolled side lobes, intercepting main beam or side lobes is easy, giving an enemy immediate ability to geo-locate an emitter. The broad beam width also limits target resolution and sensor resolution. By going to optical FC technology, a nominal IR laser with a 10 cm aperture gives a ratio of 100,000 – huge compared to RF apertures and consistent with the intuition that laser beams are narrow, focused, beams; with appropriate baffling there are no side lobes. Appendix A gives more specific numbers and also highlights that by controlling beam spread, more energy gets to the target—or sensors can detect smaller signals.

As discussed in the introduction, ubiquitous intelligence collection against America will be the norm. Besides answering the deficiencies of RMA and leveraging physics, FC uses the electro-magnetic spectrum in a way to hide our intended use. To avoid collection against us, it is advantageous to have a single small aperture type that can manifest a range of effects which we do not want an enemy to discern. Not knowing, they cannot deny or deceive collection. Major General McMaster, from the Army Maneuver Center of Excellence, indicated the Army has picked up on this theme, advocating decoupling data from our intent in order to make connections difficult for the enemy to find.[15]

For example, a final exam question the author gave to a USAF Test Pilot School radar class was to pass around a physical antenna with no other information, and ask students to discern frequencies of use, beam patterns, possible utility, and countermeasures. It opened

[†] The AWACS is the best, with an antenna size to wavelength ratio of nearly 300.

students' eyes as to how much intelligence can be collected from only physics. For timing functions, FC can be a generic black box. For optical functions, FC can appear as a generic optical window. In both cases, our intent is harder to discern.

IV. FC Technology Description

A short exposé of FC technology is important to document details, point toward specific uses, and suggest active areas of research. FCs grew from experimentation with femtosecond lasers, a technology discussed in a separate contemporary Air Force Blue Horizons research paper.[16] FC technology began to show in patent filings as early as 1998,[17] and in 2005, a Nobel Prize was given for advances, "including the optical frequency comb technique"[18] which gives, "…unthought of possibilities to investigate constants of nature, find out the difference between matter and antimatter and measure time with unsurpassed precision."[19] One researcher was given a Presidential Research award in 2011,[20] and the Department of Commerce Silver Medal in 2011,[21] representing broad impact on our society.

Technical advantages to military users will fall into three categories, and explaining each constitutes the next three sections of this paper:

1. Time, space, and position information (TSPI) from FC on the order of 10^{-18} sec is precise enough to phase-lock optical emitters ($6x10^{14}$ Hz) with a phase noise of 0.0001 degree. Synthetic *optical* arrays similar to synthetic *radio* Actively Electronically Scanned Array (AESA) antennas can be developed that use separate aircraft or satellites. This is an enabling technology for the next two areas.

2. Using lasers as a transport mechanism, signals that range from radio frequency to ultraviolet frequency can be deposited on a remote target, with previously impossible physical precision. Jamming will be possible. Injecting spoofed signals may be possible.

3. Using FC, remote sensing of physical and biological properties will be possible at microscopic levels with unheard of resolution, allowing fingerprint-like capability to identify and track materials or objects or people at a distance.

Considering first the Time, Space, Position Information (TSPI) accuracy, FC will be able to replace GPS in GPS-denied areas for timing keeping. The uniformity of the comb's mode spacing has been verified to a level below 10 parts in a quintillion (a billion billion).[22] "Stabilization of [the frequency] to a few millihertz is more than adequate, as it yields a fractional frequency noise of $< 10^{-17}$ for an optical carrier."[23] Using this precision to combine phase coherent emitters, they can be distributed over separate platforms rather than spreading over centimeters on the same physical construct as seen with an AESA radar.

Separate sources geographically distant and mobile can cooperatively transmit or cooperatively listen, forming a large virtual array. Similar to the way the individual Transmit-Receive modules of an AESA radar combine to make one cooperative aperture, time resolution of frequency combs will allow RF and optical emission from separate sources to be synchronized. Imagine a dozen or more aircraft or satellites or surface stations coherently emitting the same signal in a way to gain precision, power, sensitivity and agility. The concept is similar to the Very Long Baseline Array (VLBA) of radio telescopes spanning 5351 miles across the United States, which allows observations of an object to be combined, emulating a telescope with a size equal to more than 5000 miles in diameter![24]

Benefits Of Dispersed Synthetic Arrays

- Precision targeting
- Distributed power source
- Centralized power application
- Robust diffuse survivability
- Graceful degradation
- Conformal apertures

In the context of the Air Force, a swarm of UAVs could cooperate to be one super antenna. In the optical realm, the concept is to have separate nodes cooperatively control the phase of light similar to how the discrete segments of a Fresnel optic combine and direct light. Because of the precise timing, multiple signals onto one target can combine to generate one optical or RF signal. In the out years, imagine 24 flashlight sized laser sources on UAVs combining to create an RF signal source at arbitrary locations in space or on the Earth's surface, or collecting intelligence from centimeter sized target zones. If a satellite is attacked this way, a jamming signal cannot be nulled because the signal is generated locally rather than from a distant point source.

Because the apertures can span large distances, one can see the aperture to wavelength ratio increases by thousands, meaning the sampling size or target resolution can improve by a proportional amount. At the same time, signal strength adds linearly with the number of emitters in an array, allowing distributed power to aggregate. When conditions are correct, the entire concept of an aperture becomes obsolete when coherent energy is deposited from multiple directions around a target – the antenna aperture has functionally enveloped the target.

The ability to concentrate effect has always been a tenet of Air Force centralized control and decentralized execution. Now, in new ways, decentralized sources and aggregated effects honor the Air Force concept of concentrating power from decentralized locations.

More subtle than physics are the operational advantages. A diffuse optical or RF source is nearly impossible to counter. If an enemy wanted to attack a diverse array of emitters, the only plausible way using physics would be an Electromagnetic Pulse (EMP) weapon. This may not be possible since EMP weapons loose effect proportional to range squared, and FC weapons/sensors loose very little power over range in clear atmosphere or in the void of space (See Appendix A). Like the Greek Phalanx with spears, FC simply reaches out farther to make first contact.

A second operational advantage is that there is no requirement for FC point sources or sensors to be fixed sites. An arbitrarily large formation or swarm of emitter-listeners can be used to create dynamically allocated and shaped synthetic arrays, providing resolution on target and side-lobe control as necessary. In addition to resistance from attack, the frangible and modular design also allows graceful degradation and residual capability if individual platforms are inoperable due to Red Force attacks or Blue Force limits such as maintenance or logistics.

Lastly, because nodes combine for effect, each node can have a less intrusive conformal antenna or optical path. Something large and ungainly like an AWACS antenna on a KC-135 or an optical ball on the Airborne Laser 747 will not be necessary, giving operational freedom to use smaller platforms.

In summary, frequency comb time standards allow monstrously large synthetic apertures; giving beam agility, power on target and target resolution. In proposals for multiple platform systems, graceful degradation, linear power aggregation, and subsumptive behavior have been identified before.[25] "An important aspect of this new technology is its high degree of reliability and precision together with lack of systematic errors,"[26] which moves concepts to reality.

The significant disadvantage of these techniques is simply that they have not matured yet. Architecting command control paradigms and communication methods need to be done. What is required is not so much research to find if it will work, but engineering machinations to figure out the cost/benefit curves of the many potential options and architectures. Mesh communication, high altitude communication relay nodes, cloud computing, and appropriate mixes of automation may all be part of the solution.

Arguments can be made against any technology. However, there are often more pressing reasons to proceed.[27] It is rare that a modular and cross-platform paradigm simultaneously matches Air Force mission areas, Air Force technology investment themes, and so many acute technical and operational problems.

V. FC Used for Electronic Attack

Based on time base precision allowing dynamic encompassing apertures, uses can be divided into two categories: 1) emitting signals, or 2) collecting signals. First, cross-band weapon electronic warfare emitters will be considered. In this context, cross-banding means to emit at one band (UV, EO, IR, X-ray, Terahertz waves), and manifest an effect at a different band. Most generally this can be thought of as combining separate lasers and effecting an RF phenomena at the target. This is accomplished by heterodyning FC signals (more technical details are in Appendix B).

Combining traditional heterodyne radio concepts with FC yields something not possible before. "Multi-heterodyne spectroscopy, pioneered by Keilmann, Van der Weide and coworkers, is an elegant technique in which a second frequency comb serves as a local oscillator (LO). This LO comb has a frequency spacing (repetition rate) slightly different from that of the signal comb, so that the heterodyne beat between the signal and LO comb produces a comb in the RF domain."[28] This and other articles by Dr. Coddington have hundreds of back-citations, indicating an exploding technology base in this area.

Scientists tend to be more interested in sensing with FC rather than attacking others with FC, so the material science knowledge base necessary to convert light to other bands of EMF at a target has been minimally reported in the scientific literature. One expects that material effects induced concommitently with coherent lasers will cause demodulation. However, similar to back-door HPM entry techniques, material tips, boundaries, edges, and nonlinearities, will at least provide surrendipitous entry into target equipment.

Edges or discontinuities are almost always leaky in an electrical sense (and therefore susceptible to injected signals) because conductive discontinuities cannot be avoided. For example, in 2012, researchers reported on electron emission from metal tips.[29] This is the bane of maintenance shops responsible for stealth qualities of aircraft and pulling panels for maintenance. Where one panel ends and the other begins is always an edge that leaks electrical energy if not fastidiously cared for. Ethernet cables always plug into a separate receptacle. Even fiber optic cables are eventually terminated on an interface card and connected to something else with a metallic mating surface.

Doing electronic attack with optical beams creates a targeting and tracking problem specifically because lasers are so precise – hitting a small area with a small beam requires better tracking. However, they have a significant power advantage over RF emitters because energy is not spread out in multiple directions (Appendix A). FC techniques allow a new combination of lasers and RF that can attack electronic equipment, inject signals into aircraft flight computers, spoof or blind radars, or attack satellites from Earth.

FC opens the possibilty of depositing EMF waveforms at an adversary's front door. The entire portfolio of Electronic Warfare changes when RF or EO waveforms are created at the sensor or antenna of an enemy aircraft, missile, or ground radar site. Denial of service or jamming is only the beginning; spoofed signals may be injected while standing off on terrain, or from long duration UAVs, or from an orbit overhead. In atmosphere-free regions of space, where there is no atmospheric disturbance to light transfer, spoofing will almost certainly be possible in addition to jamming.

VI. FC Used for Collection

Instead of inducing signals on a target, the other broad category of military utility includes collecting information from targets or survey scanning areas of interest. This activity could be as simple as remote chemical sensing of nuclear effluent, presence of IEDs, or spectral identification of enemy equipment exhaust fumes – all of which have been done to some degree already. Much more is possible.

As the needs of a fast OODA loops drive the need for real-time intelligence, being able to identify certain mobile Transporter Erector Launchers (TEL) based on multi-spectral analysis of their paint is just the beginning. Increasingly it's the time-domain behavior of the TEL (for example) that is important. A Nobel Prize winning researcher wrote that, "Rapid acquisition of a complex spectrum opens up interesting possibilities in terms of broadband spectroscopy of dynamical chemical or biological systems."[30] What this means is in addition to *presence* of a TEL, the actual *operating mode* could be discerned by monitoring acoustic or RF or chemical effluent signatures. Even tracking physical markers associated with individual people may be possible. Using sensing methods instead of injection methods, the electronic discontinuities discussed in the previous section become vulnerabilities where subtle signal collection can yield a bonanza of operational implications. As referenced earlier, Israeli researchers showed the ability to monitor a running computer and determine algorithms executing in computer memory. It is feasible to expect that monitoring network connectors, it will be possible to determine network traffic.

Non-Cooperate Target Recognition (NCTR) has been used to identify everything from spinning jet engines to the walking gait of humans.[31] It is expected that biological or RF or acoustic or vibrational signatures of nearly everything with moving parts could be obtained.

Considering the physical range and geometric precision of lasers, this offers phenomenal stand-off capability to determine identity and operation mode of targets. The Big Data handling problems discussed earlier remain true, but the physics predict expansive NCTR will be possible by 2040.

On the macro scale, by carefully controlling the timing and distance between satellites, civilian researchers have been able to detect underground water reservoirs due to gravity changes when flying over. With increased time-base precision offered by FC, plus the increased sensing array size possible with FC, it is within the realm of believable to detect underground storage facilities or command posts from space.

In fact, perusing the Defense Intelligence Agency set of 7 MASINT disciplines on Wikipedia across the spectrum of Electro-optical, Geophysical, Radar, and Material physical phenomena,[32] it is hard to find a technique that cannot be done with better fidelity, better physical resolution, and from further away using frequency combs.

The disadvantages of using FC are what a Program Manager and laser physicist might predict. Development cost is required. In an austere fiscal environment, adversaries may be able to field systems faster with less testing,[33] and we need to consider defensive technical measures or procedures that mitigate this superb technology. Because of the chosen transport frequencies (visible and IR), atmospheric weather may be detrimental. Various researchers study which laser frequency is optimal under different conditions[34] and with FC, there is agility to choose frequencies of choice. Nonetheless, short of moving transmission paths into space, there will always be amplitude loss and frequency / phase noise on signals due to atmospheric behavior.

Another disadvantage is that FC sensors will produce volumes of data heretofore not conceived. We are already having trouble making high definition high refresh rate image maps of the earth available to operators for targeting or navigation. To fully integrate the capability of FC, data must be quickly processed by the intelligence community, the operators, the command and control structure, and the tactical shooters – on timelines our software programs and organizational paradigms currently do not allow. Some Big Data problems can be mitigated with automation, yet "a second key finding to emerge from Technology Horizons [published by Office of the US Air Force Chief Scientist] is that natural human capacities are becoming increasingly mismatched to the enormous data volumes, processing capabilities, and decisions speeds that technology either offers or demand."[35]

Advantages of FC sensors may be more significant than the liabilities. The adversary will not know what frequencies to deny or deceive, ranging from acoustic up to beyond visible. Sensing with FC can always be covert, and sometimes clandestine, making it doubly difficult to deny or deceive accurate detection.[‡] Lasers can build images using scanning technology, constructive aspect angle like a compound eye, or using focusing optics. Depending on the nature of the engagement and distance between, any of these might be the right engineering solution. Lasers allow power on target with tight collimation, and therefore they allow minimal chance of adverse intercept off-axes.

Another unique advantage program managers will value is that modifications to FC hardware will probably not require significant hardware changes because so much is defined in software; common emitter and collection apertures can be used across platforms. Once an airframe has integrated a suitable optical window, changing wavelength or changing modulation schemes or swarming algorithms or control functions would be in software, not hardware. Low-

[‡] Covert operations can be in the open, but conceal the intent or sponsor with plausible deniability (USC Title 50 Section 413b(e)). A clandestine operation places emphasis on concealment of the operation rather than on concealment of the identity of the sponsor.

speed aircraft can use common turrets like the Directional Infrared Counter Measures (DIRCM) or Large Aircraft Infrared Countermeasures (LAIRCM) pods, while supersonic aircraft will have unique integration issues to critical airflow requirements that may be solved with conformal windows.

VII. Implementing FC

Exquisite timing, synthetic arrays, electronic attack, and sensing are intriguing theories. However, "It is relatively easy to come up with ideas, but implementing them is another matter entirely."[36] Shown in the text box, there are four facets of implementing FC that may delineate the character of doing so.

First, is the year 2040 (27 years from now) a reasonable look forward and expectation for this advanced military use of FC? Yes. In 2005, a Nobel Prize was given for frequency combs.[37] As a comparison, a Nobel Prize was given in 1956 for "transistor effect." Twenty-seven years later, Intel and Motorola came out with their 80286 and 68020 CPUs with 134,000 - 200,000 transistors on a single integrated circuit die, each only 1.5-2.0um in size.[38] With analogous advances, twenty-seven years past 2005 everything predicted in this paper could be attained plus more.

> Implementing Frequency Combs
>
> - Timing of Technology Progress
> - Modular vs. Enterprise
> - Physics Challenges
> - Acquisition Community Recommendations

A second feature of FC implementation is that modular solutions seem to offer the best benefit. As itemized earlier, there are advantages of diffuse flock self-protection, graceful degradation, scalable resolution and power. Liabilities include a logistic and maintenance trail of potentially 100s of emitters, but this may be no more than maintaining T/R module spares for AESA radars.

Smaller modular systems distributed on multiple airborne platforms requires modest power, weight, and size requirements. Moving in this direction, compact laser frequency combs have been developed that are no bigger than a shoebox.[39] Future expectations of frequency combs are for integrated circuit versions.[40] This progress is analogous to the function of vacuum tubes being reduced to transistors then integrated circuits.

Thirdly, dealing with real world physics will challenge implementation. Atmospheric path scintillation (200-300 Hz atmospheric changes) will affect laser transit. Adaptive optics have been used to pre-compensate phase disturbances across the focal plane of imaging optical systems. However, FC timing functions can nominally tolerate large amounts of phase noise on laser links, so scintillation may not be significant in that application. For heterodyne applications where phase noise is important, it may be the difference between injecting high fidelity spoofing signals and random barrage jamming signals. Atmospheric problems may be mitigated by non-linear phenomena of ultra-short lasers, allowing energy to conduit through filaments across long distances – similar to electrical conduction through lightning bolts.[41]

Information is encoded in the frequency spectrum, and unintended amplitude or phase modulation may be a secondary effect such as "static" on the recovered signal. This is analogous to the common experience of an FM radio receiver exhibiting less static than an AM receiver. If atmospherics become too challenging, laser use does not have to be terrestrial and endure a hostile optical atmosphere.

Lastly, there are several aspects of managing the acquisition strategy for FC worthy of mention. First, after consideration of other options, it seems a material solution is the right way to gain the new capabilities. No amount of doctrine, re-organization, training, leadership, education, personnel, or facilities change (DOTLPF) can replace physical optical capability that is only recently discovered. Though research and material solution will be necessary, FC does not need significantly different equipment to address different threats or purposes. All the timing functions, transmit tools such as spoofing IADS, barrage jamming, or creating voice traffic, and all the sensing applications, may be possible with the same UAVs with different software loads – "there's an app for that."

We are at a point now where the technology "early adopter wedge" can give us an advantage for a window of time[42] when we could mature tactics while adversaries are still developing capability. Some authors warn, "The probing creativity seen in [the US Military] is counterbalanced by force development programs that assume constancy in the type of threats and the nature of U.S. objectives."[43] If we do not learn to understand FC capability from an offensive and defensive point of view, and possibly adjust our related objective, adversarial threats will get ahead as they adopt these capabilities.

It is important to build this technology into acquisition program documentation, recognizing that operational use may be around the corner, given a Technical Readiness Levels of about 4. The Joint Capability Integration Development System (JCIDS) may include generic capability requests such as "jamming or spoofing enemy IADS" that can be met with FC, however the additional operational and strategic capabilities are not spelled out because nobody knew prior that they were possible.

VIII. Strategic Implications of FC

New capability is not the same thing as new strategy. Making that bridge will require significant effort. If we value the advantages of FC and are able to manage the possible concerns, maturing FC technology and tactics have strategic implications to how America can advantageously equip and employ national military force. "Strategy without tactics is the slowest route to victory. Tactics without strategy is the noise before defeat."[44]

> Strategy Implications for Air Power using Frequency Combs
>
> - Vulnerability Testing
> - America's Grand Strategies
> - Deliberate Planning Phase 0
> - Air dominance changes

First, we need to address frequency comb technology from a defensive point of view and assess our processes and system vulnerabilities. Battle damage assessment is difficult with Electronic Attack because the only way to tell if we have been attacked requires sophisticated correlation of sensed events during a conflict. For example, was the bogus detection on the search radar a software glitch or was it an EW attack? Doing this is hard enough in a controlled environment like the Air Force Test Center Benefield Anechoic Chamber or closed range like the Navy's China Lake. For open air conflicts, we are not well equipped to do defensive MASINT in real-time, so it is imperative we know our equipment well before it is deployed and vulnerable. This means the developmental and operation test communities need to assess our process and system vulnerabilities in light of this new threat.

Secondly, contemporary shifts in American Grand Strategy are consistent with characteristics of frequency combs and should leverage the new technology. All four major forms of post-Cold War Grand Strategy (Disengagement, Power Balance, Primacy, and Liberalism)[45] de-emphasize kinetic denial and punishment and emphasize deterrence and coercion. More bluntly, Sun Tzu wrote, “All warfare is based on deception.”[46] Frequency combs excel in this area, and allow a wider repertoire of operational plans and tactical engagements consistent with strategic goals of the nation.

Thirdly, when Time-Sequenced Aggregate Data (TSAD, see section Understanding the Future) has become the center of gravity of intelligence collection and knowledge, battlefield preparation will include new offensive and defensive requirements that frequency combs (FC) can answer. Though technology points this way, America’s laws are lagging behind. It is not clear what organization would manage or execute such activities and whether they would fall under USC Title 50 activities (War and National Defense nominally operated by civilian agencies) or USC Title 10 (Armed Forces nominally operated by the Department of Defense).

Consider Reiter’s bargaining model of war, which teaches that engagement with an enemy is ontologically equivalent to learning about them.[47] Because of TSAD pervasiveness, we cannot wait until war-time to make strategic efforts to prevent *their* knowledge and build *our* knowledge. Recent changes that correlate with conflict are too easily correlated with mal-intent.[48] It is important to counter TSAD technologies by controlling *pre-conflict* data.

It is important to create a steady peacetime corruption of an adversary’s ambient TSAD so that anomalous war-time presence does not raise any flags. For example, several times a day or a week, FC can be used to interrupt or deny or create behavior in an enemy’s system that is trained to be normal. This is probably not human training, but rather autonomous systems on their side, learning what “normal” looks like. By modifying their knowledge of normal, our war-time activity can slip through.

By analogy, we must raise the “noise floor” of knowledge and information for adversaries during peacetime, similar to how a jammer raises the real-time RF noise floor. The ability to be covert or clandestine or tunnel kinetic weapons into battle space controlled by the enemy during a kinetic war requires us to pre-enable these activities with activity during peacetime.

Reaching out and touching enemy systems to create habits of anomalies or behavioral norms requires covertly affecting their systems repeatedly during peacetime. FC from space borne platforms seems most amenable to this task, but other serendipitous opportunities should not be overlooked. Because using FC as sensors or to do signal infiltration can be precisely targeted and offers little chance of detection, FC is an enabling technology that can be engaged forward in peacetime to enable a better fight forward in wartime.

In prior centuries, America has benefited from borders on two oceans and two friendly nations. With the advent of cyber and FC effects from space, America is not isolated. It now has as many borders as it does enemies. Sensing and EW techniques can be executed with impunity. This removes the A2AD problem for us and yet if the technology is turned against us, it removes our own A2AD benefit we have enjoyed for two centuries.

The significance of TSAD predicts Phase 0 (shaping the battlefield) of Operational Plans will become more significant to the overall outcome of war.[49] Phase I (deterrence) will not depend on a new show of force but rather on intentional cultivation of seeds we have sown during Phase 0. Phase II will be less about seizing initiative and more about confirming the adversary cannot. Overt dominance of Phase III will be muted on the world stage because neither side can endure the appearance of initiating violence or the economic fallout of having done so. Stabilization in Phase IV and enabling civil authorities in Phase V will be more about releasing control of the situation to those parties we wish to support.

Last, strategic concepts of air dominance will change. As exhibited in the 1967 Arab-Israeli war and the 1991 Iraqi war, not having air dominance over a theater of conflict is correlated to losing.[50] However, after WWII up until recent times, we have associated control of the airspace over a theater an important antecedent to winning. That may no longer be true. It is not conceivable that we will be able to prevent enemy sorties over China or Russia or any significant state-on-state engagement where the enemy has air assets. In light of this, another Air War College professional study paper is presenting concepts of briefly taking down enemy IADS or transiting it so quickly so as to not matter.[51] Using FC during Phase 0 of a conflict and during hostilities may be a significant part of electronic warfare techniques opening up safe routes of ingress and egress.

Three examples may clarify the breadth of strategic concepts that will change. The center of gravity surrounding America's conflict with Iran is about nuclear monitoring. FC techniques would allow us to measure material properties of remote objects and chemical effluent in order to track equipment and personnel of interest during production processes of nuclear material. This avoids strategic complications of being in country and we would appear patient and accommodating on the world stage.

The China conflict is characterized by their slow and methodical expansion – geographically, militarily, and economically. The differential steps are each small enough to not incite military response when combined with the deterrence effect of their improving military. The cumulatively aggressive nature of such a latent adversary can be dissuaded or deterred if they lose confidence in their models of conflict engagements – in other words, if the risk of American response becomes too high. Peacetime application of FC methods on radar sites, or electrical control systems, or potential to jam or control IR and RF air-to-air missiles and new

IR/RF cruise missiles and anti-ship cruise missiles, would reduce their confidence and dissuade their next incremental move.

National Security issues of Russia involve regional hegemony in political and economic ways, leveraging unique resources they can offer. It would soften their economic hegemony in the realm of energy supply if we can interfere with SCADA at factories and distribution methods. Ambivalent nations like Ukraine may find reason to shift to sustainable technology associated with the West. In less stable regimes, timely interference with national infrastructure may encourage the changes America is hoping for.

IX. Conclusion

If cultivated as a military tool, frequency comb technology will shatter prior paradigms with new capability, and military use of frequency combs is viable in the technology framework of the next 25 years. They are consistent with fiscal realities and the types of conflicts we expect. Clandestine operations are possible, and the technology offers intrinsic covert character. This allows operation in contested environments, even when each side has tremendous sensor data from the other side. In the face of A2AD strategies of an enemy, American can sense and target ID, and apply signals dominance in a world defined by Big Data by using frequency combs.

Notes

1. Brenner, *America the Vulnerable*, 163.
2. Hänsch, *Frequency Comb Research*.
3. Orzel, *Amazing Laser Applications 11: Frequency Combs!*
4. Hänsch, *Frequency Comb Research*.
5. Hänsch, *Frequency Comb Gallery*.
6. Chief Scientist of the Air Force, *Technology Horizons*, 68, 97.
7. Ibid., 51.
8. Ibid., 50.
9. Mork, *Subsumptive Satellite Constellations*.
10. Metz and Kievit, *Strategy and RMA*.
11. Brenner, *America the Vulnerable*, 201.
12. Metz and Kievit, *Strategy and RMA*, 19.
13. Ibid., *Strategy and RMA*, 12-17.
14. Henrikson, *NATO's Gamble*, 197.
15. McMaster, Air War College lecture.
16. Bohenek, *Femtosecond Lasers*.
17. van der Weide and Keilmann, *Coherent Periodically Pulsed Radiation*.
18. Nobel Prize Organization, *The Nobel Prize in Physics 2005*.
19. Nobel Prize Organization, "Popular Information", 5.
20. National Institute of Standards and Technology, *Presidential Early Career Awards*.
21. National Institute of Standards and Technology, *Department of Commerce Silver Medal*.
22. Ye, *Frequency Combs Principle, Operation, Applications*, 24.
23. Ibid., 28.
24. Wikipedia, *Very-long-baseline Interferometry*, 2014.
25. Mork, *Subsumptive Satellite Constellations.*
26. Ye, *Frequency Combs Principle, Operation, Applications*, 28.
27. Metz & Kievit, *Strategy and RMA*, vi-vii.
28. Coddington, C. and Newbury, *Spectroscopy Using Frequency Combs*, 1.
29. Thomas, Holzwarth, Hommelhoff, *Few-cycle Pulses for Nanoscale Photoemission*.
30. Coddington, C. and Newbury, *Spectroscopy Using Frequency Combs*, 2.
31. Wikipedia, *Radar_MASINT*, 2013.
32. Wikipedia, *MASINT*, 2013.
33. Chief Scientist of the Air Force, *Technology Horizons*, 131.
34. Sprangle, *Optimum Wavelength…in Various Atmospheric Environments*.
35. Chief Scientist of the Air Force, *Technology Horizons*, 131.
36. Arnold, *What Make Great Leaders Great*, 74.
37. Nobel Organization, *Nobel Prize in Physics 2005*.
38. Wikipedia, *Transistor_count*, 2013.
39. Photonics.com, *Compact Frequency Comb*.
40. National Institute of Standards and Technology, *Comb on a Chip*.
41. Bohenek, *Femtosecond Lasers*.
42. Metz and Kievit, *Strategy and RMA*, 13.
43. Ibid., 30.

44. Sun Tzu, *The Art of War*.
45. Dueck, *Reluctant Crusaders*, 115.
46. Sun Tzu, *The Art of War*.
47. Reiter, *Bargaining Model of War*, 31.
48. Brenner, *America the Vulnerable*,189.
49. Joint Chiefs of Staff, *JP 5-0 Joint Operational Planning*, III-39, III-41.
50. van Creveld, *Rise and Fall of Air Power*, 52.
51. Rogers, *CONOPS of Strike in 2040*.

Bibliography

Arnold, Frank. *What Makes Great Leaders Great.* New York: McGraw Hill, 2012.

Asst Secretary of Defense for Research and Engineering (ASDR&E). "Communication technologies including smartphones and laptops could now be 1000 times faster." *S&T News Bulletin.* March 07, 2012. http://www.acq.osd.mil/chieftechnologist/publications/docs/ST_NewsBulletin-V2-I11(16MAR2012).pdf (accessed October 10, 2013).

Bohenek, Lt Col Brian. *Militarization of Femtosecond Lasers: Maintaining an Assymetric Advantage in Future Anti-Access/Area Denied Enviornments.* Blue Horizons Research Paper, Air War College, February 2014.

Brenner, Joel. *America the Vulnerable.* New York: Penguin Press, 2011.

Business Staff Writer. "Mullins: Tracking Point Introduces a Rifle With Nearly Foolproof Accuracy." *The Tampa Tribune*, November 2013: http://tbo.com/news/business/mullins-trackingpoint-introduces-a-rifle-with-nearly-foolproof-accuracy-20131103/.

Chichowski, Lt Gen Kurt. *Air War College luncheon.* Maxwell Air Force Base, September 17, 2013.

Chief Scientist of the Air Force. *Technology Horizons.* Maxwell AFB: Air University Press, 2011.

Clausewitz, Carl von, and Michael and Paret, Peter ed Howard. *On War.* Princeton, New Jersey: Princeton University Press, 1976.

Coddington, Ian, William C. Swan, and Nathan R. Newbury. "Coherent, Multi-heterodyne Spectroscopy Using Stabilized Optical Frequency Combs." July 2010. http://arxiv.org/ftp/arxiv/papers/0710/0710.3404.pdf (accessed October 5, 2013).

Department of Defense. "Joint Operational Access Concept." *U.S. Department of Defense.* January 17, 2012. www.defense.gov/pubs/pdfs/joac_jan%202012_signed.pdf (accessed October 09, 2013).

Dillow, Clay. *Intelligent Rifle Lets You Pre-Tag Your Target, Then Fire When Ready.* November 29 , 2012. http://www.popsci.com/technology/article/2012-11/new-intelligent-rifle-scopes-make-every-trigger-pull-perfect-shot (accessed 12 5, 2013).

Dueck, Colin. *Reluctant Cruisaders.* New Jersey: Princeton University Press, 2006.

Foxman, Simon. *Quartz.* July 18, 2013. http://qz.com/105463/this-is-what-a-destabilizing-cyberattack-on-financial-markets-would-look-like/# (accessed October 9, 2013).

Gantz, John and Reinsel, David. *The Digital Universe in 2020: Big Data, Bigger Digital Shadows, and Biggest Growth in the Far East.* White Paper, Framingham, MA: IDC / EMC Corporation, December 2012.

Gantz, John F. *The Expanding Digital Universe.* IDC Whitepaper sponsored by EMC, Framingham, MA: IDC, 2007.

Gates, Robert. "Science and Technology (S&T) Priorities for Fiscal Years 2013-17 Planning." *Office of the Secretary of Defense ACQWeb.* April 19, 2011. http://www.acq.osd.mil/chieftechnologist/publications/docs/OSD%2002073-11.pdf (accessed December 14, 2013).

Geis, John, and Grant Hammond Ted Hailes. *Technology and the Comprehensive Approach: Part Problem, Part Solution.* Center for Technology and National Security Policy, National Defense University, National Defense University, 2011, 69-85.

Genkin, Daniel, Adi Shamir, and Eran Tromer. *RSA Key Extraction via Low-Bandwidth Acoustic Cryptanalysis.* December 18, 2013. http://www.cs.tau.ac.il/~tromer/acoustic/ (accessed December 24, 2013).

Google. *Google.org Flue Trends*. February 10, 2014. http://www.google.org/flutrends/us/#US (accessed February 10, 2014).

Hänsch, Theodor W. *Gallery Frequency Comb.* August 31, 2008. http://www.mpq.mpg.de/~haensch/comb/links.html (accessed October 02, 2013).

—. *Research Frequency Comb.* September 14, 2008. http://www.mpq.mpg.de/~haensch/comb/research.html (accessed October 02, 2013).

Henriksen, Dag. *NATO's Gamble.* Annapolis, MD: Naval Institute Press, 2007.

Jodice, Lt Gen (ret) Ralph. *Air War College Briefing.* Maxwell Air Force Base, AL, Jan 27, 2014.

Joint Chiefs of Staff. *JP 5-0 Joint Operation Planning.* Government Printing Office, 11 August 2011.

Jones, Ralph Ernest. *Principles of Command.* Des Moines: Federal Printing Co., 1922.

Kaku, Michio. *Physics of the Future.* New York: Anchor Books a Division of Random House, 2011.

Markowitz, Eric. *How a Hacker Can Break Into Your Laptop With Just an iPhone.* December 20, 2013. http://www.vocativ.com/12-2013/hacker-can-break-laptop-just-iphone/ (accessed December 24, 2013).

McMaster, Maj Gen H. R. *Air War College briefing.* Maxwell Air Force Base, September 18, 2013.

Metz, Steven and Kievit, James. "Strategy and the Revolution in Military Affairs: From Theory to Policy." *Strategic Studies Institute*, 17 June 1995: 1-8; 18-32.

Mork, Brian. "Directed Energy is Different." *Intrepid Creativity.* November 14-18, 1995. http://www.increa.com/articles/directed-energy-challenges.pdf (accessed October 10, 2013).

National Institute of Standards and Technology. *Department of Commerce Silver Medal.* December 13, 2011. http://www.nist.gov/pml/div686/ultra-precise-lidar-group-receives-doc-silver-medal.cfm (accessed February 9, 2014).

—. *Future 'Comb on a Chip': NIST's Compact Frequency Comb Could Go Places.* October 25, 2011. http://www.nist.gov/pml/div688/comb-102511.cfm (accessed October 14, 2013).

—. *Presidential Early Career Awards for Scientists and Engineers.* July 23, 2012. http://www.nist.gov/pml/div686/ian-coddington-receives-pecase.cfm (accessed February 10, 2014).

National Research Center Canada. *Optical Frequency Comb - Projects - NRC-CNRC.* February 24, 2010. http://archive.nrc-cnrc.gc.ca/eng/projects/inms/optical-comb.html (accessed October 02, 2013).

Nobel Prize Organization. "Popular Information." *Supplemental Information to Press Release 4 Oct 2005.* October 4, 2005. http://www.nobelprize.org/nobel_prizes/physics/laureates/2005/popular-physicsprize2005.pdf (accessed November 25, 2013).

—. *The Nobel Prize in Physics 2005.* 2005. http://www.nobelprize.org/nobel_prizes/physics/laureates/2005/ (accessed November 25, 2013).

Orzel, Chad. *Amazing Laser Applications 11: Frequency Combs!* April 21, 2010. http://scienceblogs.com/principles/2010/04/21/amazing-laser-application-10-f/ (accessed October 14, 2013).

Photonics.com. *Compact Laser Frequency Comb Really Goes Places.* October 31, 2011. http://www.photonics.com/Article.aspx?AID=48881 (accessed October 14, 2013).

Rogers, Lt Col Henry T. *CONOPS of Strike in 2040 in an A2AD Scenario.* Blue Horizons Research Paper, Air War College, 14 February 2014.

Sprangle, Phillip, and Joseph Penano. *Optimum Wavelength and Power for Efficient Laser Propagation in Various Atmospheric Environments.* NRL/MR/6790--05-8907, Washington, DC: Naval Research Laboratory, October 25, 2005.

Thomas, Sebastion, Ronald Holzwarth, and Peter Hommelhoff. "Generating few-cycle pulses for nanoscale photoemission easily with an erbium-doped fiber laser." *Optics Express*, 20:13 (2012) : 13663-13668.

Ungerleider, Neal. *How Vocativ Mines the Deep Web for Storytelling.* December 23, 2013. http://www.fastcompany.com/3020671/how-vocativ-mines-the-deep-web-for-storytelling (accessed December 23, 2013).

United States Army. "Captsone Concept for Joint Operations: Joint Forces 2020." *National Defense University Keystone Captsone.* September 10, 2012. http://keystone.dodlive.mil/files/2013/04/CCJO-Sep2012.pdf (accessed October 09, 2013).

van Creveld, Martin. "The Rise and Fall of Air Power." *The Rusi Journal*, June/July 2011 v 156 no 3: 48-54.

—. *The Transformation of War.* New York: The Free Press - Simon & Shuster, 1991.

van der Weide, D.W. and Keilmann, Fritz. *Coherent Periodically Pulsed Radiation Spectrometer*, US Patent 5748309A. (May 5, 1998). https://www.google.com/patents/US5748309.

Weiner, Andrew M. "Ultrafast optical pulse shaping: A tutorial review." *Optics Communications*, 284 (2011): 3669-3692.

Wikipedia. *MASINT.* n.d. http://en.wikipedia.org/wiki/MASINT (accessed October 02, 2013).

Ye, Jun and Cundiff, Steven T., ed. *Femtosecond Optical Frequency Comb: Principle, Operation, and Applications.* Norwell, MA: Kluwer Academic Publishers / Springer, Sept 2004.

Appendix A – Link Budget

LINK BUDGET FOR OPTICAL TO RADIO FREQUENCY DOWN CONVERSION

If lasers will be used to illuminate a distant target, the laser signal must have enough power to get there and the laser signal must retain enough integrity or fidelity. The fidelity issue is too diverse to cover in a short appendix, and may include solutions such as adaptive optics, limited path lengths, limited transmission media, or more exotic solutions such as ionized conduction paths. This appendix addresses only the power issue, which is normally referred to as a "link (power) budget."

An RF source created in the vicinity of a target receiver suffers essentially no RF attenuation traveling to the receiver. However, it is helpful to consider how much laser energy is lost from the source to the target in order to predict the range of utility.

Laser frequency combs can be transmitted in the form of laser beams to mix and reconstruct RF waveforms at the target. We are particularly interested in frequency differencing in ambient media at a remote local target area. This is analogous to what happens in RF heterodyne receivers (See Appendix B).

First consider how much the laser light will diverge after leaving the source. [1]

$\theta = M^2 \frac{\lambda}{\pi w_0}$, where

θ = beam divergence in radians

M = beam quality (1 or higher, 1= perfect Gaussian cross-beam profile)

λ = wavelength

w_0 = radius of beam waist (approximately the exit aperture in a high f/# optical system)

Instead of requiring tactically relevant 10 KW lasers to cause thermal effects at the target, we require only much lower power levels corresponding to weak signals. Consider a 5 mW slideshow laser pointer. The exit aperture is about 1 mm squared, or about $1\text{x}10^{-6}$ m^2. The beam divergence is:

$$\theta = 1^2 \frac{532nm}{\pi * 1mm}$$

Doing the math predicts a 17 m diameter beam at 100 km. The initial source flux of 5 mW/mm^2 is reduced to $1.7\text{x}10^{-4}$ W/m^{2}, assuming a 1% efficient conversion from optical to RF. [2] Non-linear media conversions of a single laser beam to RF have tremendously less conversion efficiencies, however with frequency combs, coherent interference phenomena dominate rather than non-linear conversion phenomena. Like interference waves of pebbles dropped into a pond, it is not clear there would be any amplitude loss. With a 1 m^2 active area on the target, this would be $1.7\text{x}10^{-4}$ Watt, or -37 dBW.

1. Dr. Rüdiger Paschotta. *Beam Divergence*. RP Photonics Encyclopedia, 7 April 2013. http://www.rp-photonics.com/beam_divergence.html. (Accessed 9 October 2013).

2. 5 mW/mm^2 * $(1/17)^2$ * (1W/1000mW) * $(1000mm/1m)^2$ * 1%

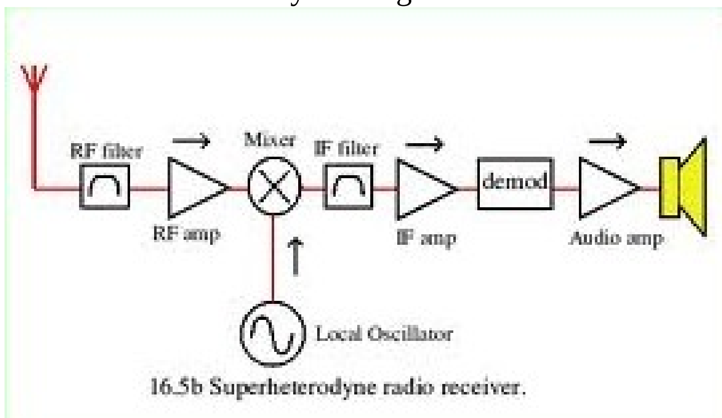
Antennas and receiver-amplifiers are designed to collect RF energy out of the atmosphere at a level of roughly -90 dBW to -110 dBW. This very sensitive nature is required because the RF energy typically travels very far, has spread out geometrically, and lost almost all of its power.

Comparing what is available (-37 dBW) to what is required (-100 dBW), the laser would deposit roughly 10^6 or 1 million times more energy than we need in order to be sensed by the target antenna, easily swamping their intended signal. This example was done at 100 km range. If there were no energy loss in transit (only spreading), we could shoot from 1,000 km or more miles away.

Laser physics seems to indicate delivering energy to an adversary's land-based defense radars, airborne radars, or missile seeker heads is not an area access problem. Instead, the largest problem may be atmospheric interferences and target tracking.

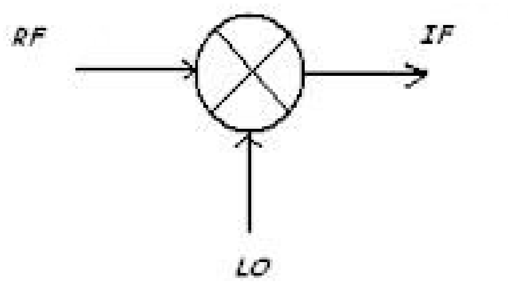
Appendix B – Heterodyne

Heterodyne radios have been in use since the early 20th century and a majority of modern radio frequency (RF) receivers use a heterodyne design.



http://www.st-andrews.ac.uk/~www_pa/Scots_Guide/RadCom/part16/page4.html

A filtered and amplified (RF) signal is combined, or mixed, with a stable reference RF signal local oscillator (LO) generated at the receiver. When combined in a mixer such as a diode or transistor, an intermediate frequency (IF) signal is generated that is the difference between the received RF and the LO.



http://rf-circuits.info/radio/rf-mixers/

The name "IF" comes about because it is only an intermediate to the final desired signal. The IF signal is subsequently amplified, filtered and processed in other ways, and then demodulated to recreate the frequency variations that come out as the audio signal of the radio.

Using frequency combs, instead of an RF carrier frequency mixing with an RF LO, the optical carrier frequency is stable enough to mix with an optical frequency LO and down convert to an RF that can then be used by any RF receiver.