The Past, Present and Future
of
Secondary Radar

Ed Gellender

Guidelines

- There is a lot of material to cover.
  - This subject would make a good 15 week course (although I don't think there is such a course). We have an hour or two. It has to be a "mile wide and an inch deep."
  - I am putting understanding over accuracy. Do not bother calling me out on my lies; God will surely punish me for this.
  - Time permitting, I will try to take brief questions
- We will primarily cover current work in IFF, but a little history adds a lot of perspective. Upcoming changes are briefly addressed.

Chapter 1: How did it get started?

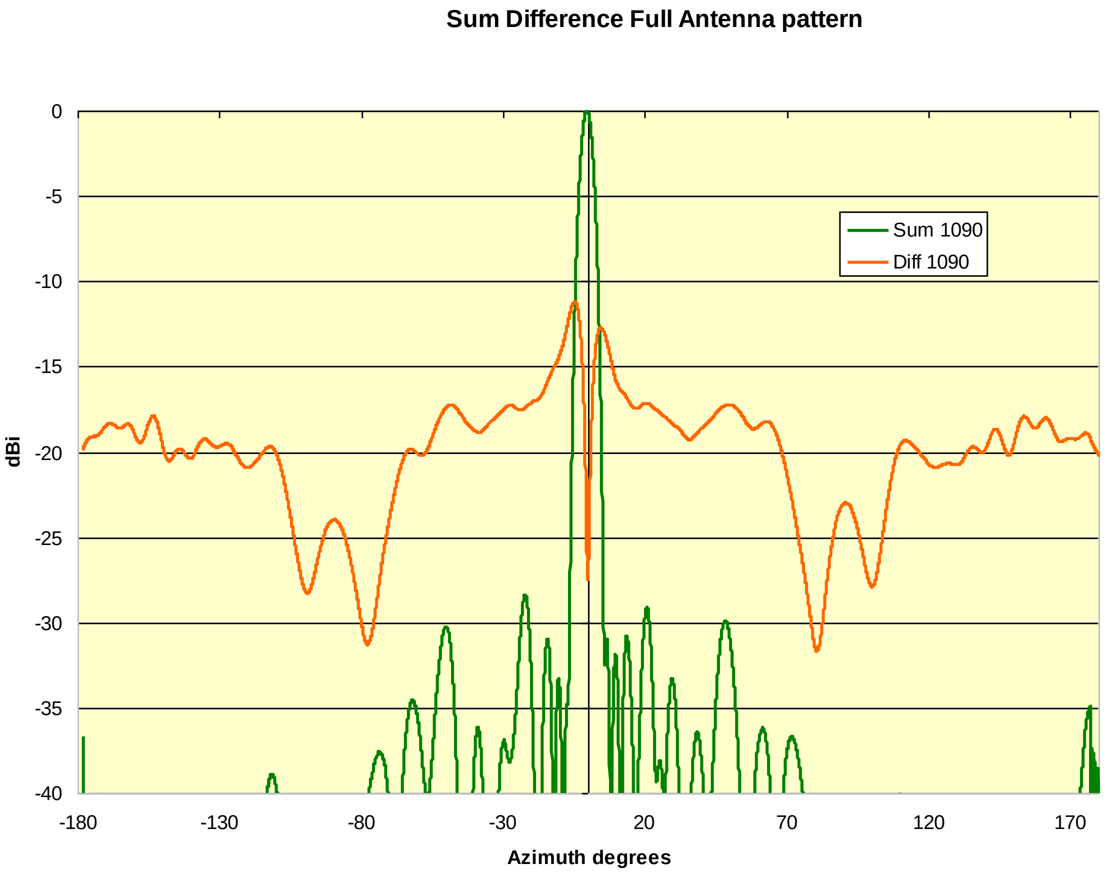
1939 – 1942: Radar goes to War

- **“Radio Detection and Ranging”**
  - During “the Blitz,” the Chain Home System gives London warning of incoming bombers to ready defenses.
  - Indicated presence, range and direction of incoming aircraft (actually radar echoes from hunks of metal in the air)

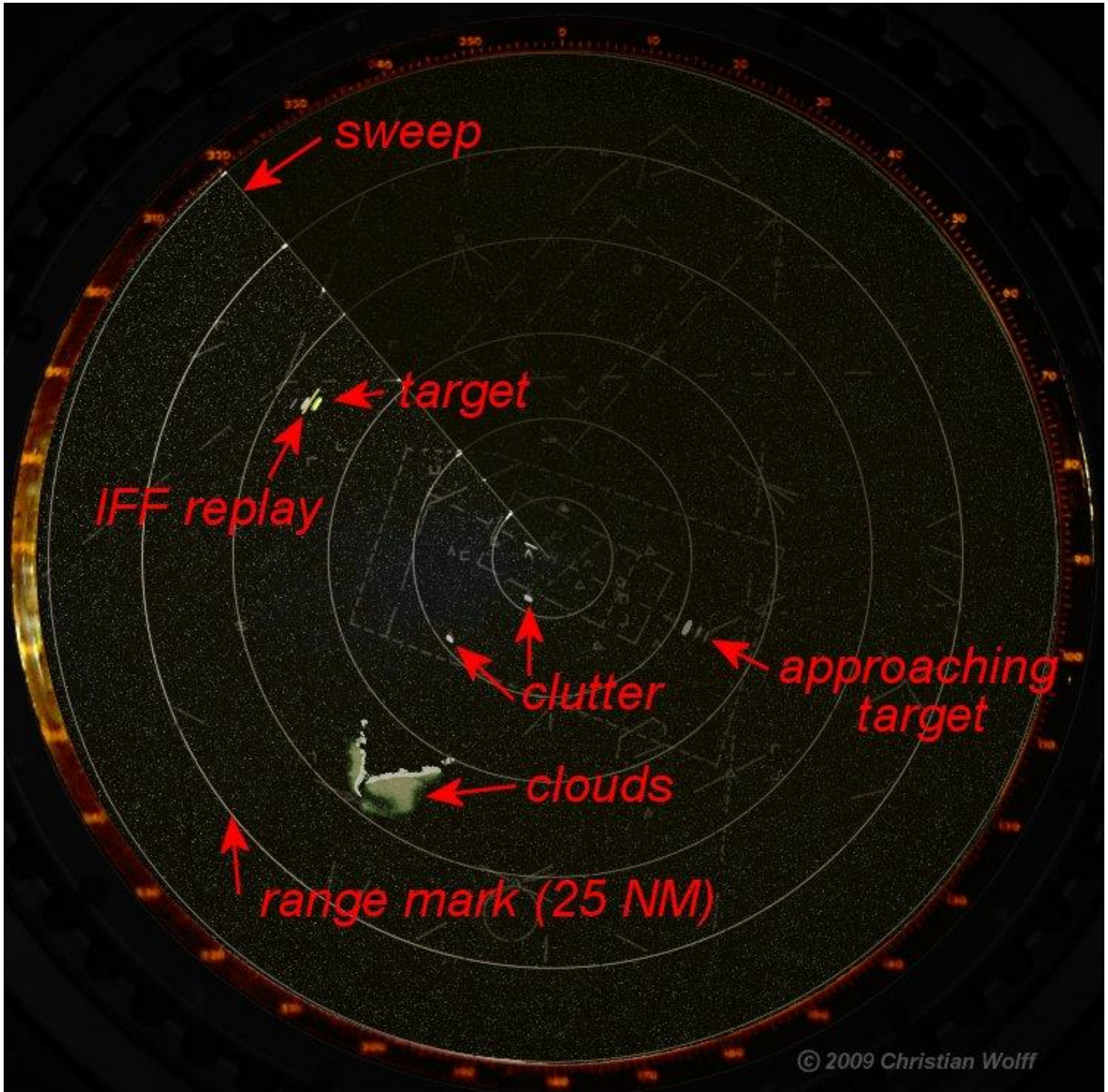
- **Spitfires Rising: Defensive action requires combat control of interceptor aircraft.**
  - “Identification Friend or Foe” …or IFF
  - Which blips are from our hunks of metal? Which are from their hunks of metal?
  - {*next 2 slides – Typical radar antenna and pattern}*
  - Radar repeaters on friendly aircraft provides double arcs
  - *{following slide – Radar / IFF display}*

Typical (modern) Radar / IFF ATC Antenna

Representative IFF Antenna Pattern



Representative early Radar Display



1944: A war of competing technologies

- **Radars proliferate over the entire spectrum**
    - More advanced radars use different frequencies for different applications
    - Both sides learn how to exploit the other's systems
    - Becomes too complex for radar repeaters to accommodate all radars
- **Allies dedicate specific frequencies to IFF**
    - Controllers get 1030 MHz Interrogators
    - Aircraft get transponders that reply on 1090 MHz (squawk)
    - Still in use today
    - Add individual aircraft identification number (squawk code)
- **Pulse Amplitude Modulation – A series of 1 uS pulses**
    - Interrogation: Two pulses, closely spaced
    - Reply: Two widely spaced pulses that bracket a series of 12 slots
    - If a slot has a pulse, it is a 1; if not it is a 0

Chapter 2: Civil Air Traffic Control from 1960 until today

Philosophy 101

- **How Safe Does the Air Traffic Control System Have to Be?**
  - Taking the kids to see Grandma? ….
  - That is what “Failure is not an Option” **REALLY** means!
  - Some years there are zero commercial air fatalities
  - We have achieved near perfection….
    - DON’T BE THE ONE WHO MESSES IT UP
  - Events like Malaysia Air 370 are the exceptions that prove the rule

Alphabet Soup - Acronyms

- **ATCRBS** (“at–crabs”)
  - **A**ir **T**raffic **C**ontrol **R**adar **B**eacon **S**ystem
  - Overall FAA Civil Air Traffic Control
- **En-route Control Centers**
  - Maintain radar/IFF control of aircraft at altitude across the country
- **TRACON** (“tray–kon”)
  - **T**erminal **R**adar **A**pproach **Con**trol
  - Specific patterns for departure and approach
  - Different controllers assigned different patterns

Basic IFF Modes

- **Mode 3 - Aircraft Identification**
  - Crew enters assigned 4 digit octal number code into transponder
  - 3 bits per digit, 0000-7777, 4096 possibilities
  - A few special codes are reserved:
    - Emergency, radio failure, hijack; non-controlled
- **Mode C - Aircraft Altitude**
  - Height finding techniques are complex and not accurate enough, so we need something better
  - Oh, right … We have access to the altimeter
  - Same as Mode 3, but 12 bits of gray coded data

Interrogation Signals-in-Space

- **Interrogation**
  - PAM - Two 1 uS pulses separated by:
    - (Mode 1: 3 uS – discussed soon)
    - (Mode 2: 5 uS – discussed soon)
    - Mode 3: 8 uS
    - Mode C: 21 uS
- **Replies**
  - Same Pulse modulation as interrogation
  - Two “bracket” pulses straddle a series of twelve slots
  - If a pulse is in a slot it is a 1; otherwise a 0
  - All replies are in the same format; Interrogator matches the reply to the mode just interrogated

Range Calculation

- **Determining aircraft range from interrogator**
- (Don't be smug; you didn't always know this either)
  - Interrogations go out at the speed of light
  - Transponders reply in exactly 3 uS
  - Replies go back at the speed of light
  - Interrogator calculates range from total round-trip time
  - Range can be calculated quite accurately
- **PRF – Radar / IFF Pulse Repetition Frequency**
  - We know roughly how far we can detect aircraft
  - After enough time has passed that we have seen up to and above that range, we can start over again
  - The net result is that there are many transmissions while the antenna beam passes any one aircraft.
  - The resulting rate of transmissions is known as the Pulse Repetition Frequency (PRF).
  - Sometimes it is called PRI (…interval) or PRP (…period)

Limitations:

- **Multipath**
  - At radio frequencies the world is a hall-of-mirrors; They bounce off everything (picket-fencing on your car radio, anyone?)
  - Each transmission can arrive via several different paths at different times
  - The fastest one is always the right one – the straightest path
  - Multipath affects both uplink and downlink
  - Interrogators have to remove redundant responses. Ain't easy, but it can be done.

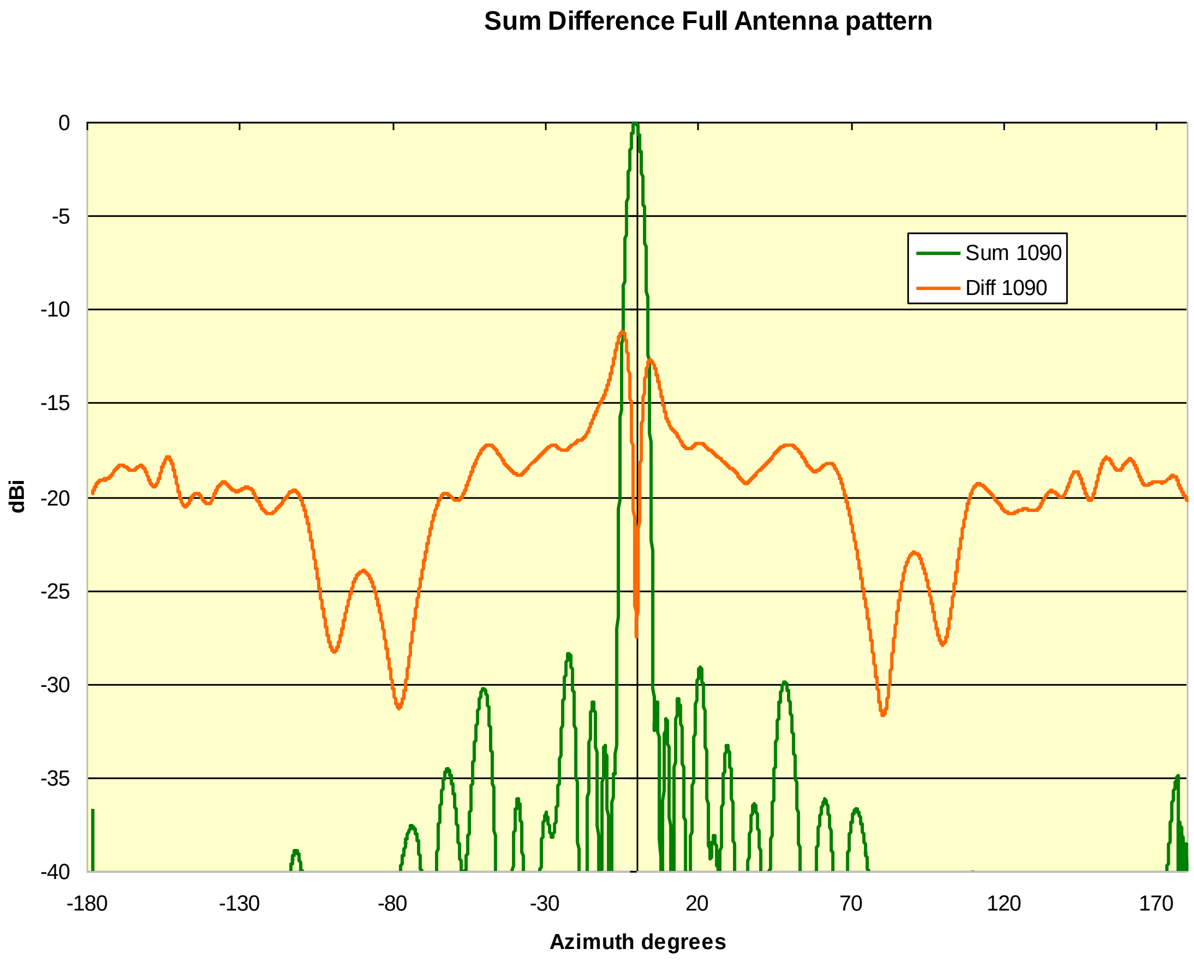
More Limitations

- **FRUIT**
    - Transponders reply to any interrogator they hear
    - Question: Is that reply meant for me or someone else???
    - The reply clutter I don't want is called FRUIT
    - High traffic density can result in enough FRUIT to overload the air traffic control system. Serious issue for the FAA.
- **DE-FRUITING**
    - Each target is interrogated many times in an antenna pass
    - Proper replies are always very close in range
    - Adjacent replies within range tolerance are accepted
    - Lonely, one-of-a-kind replies are rejected. (like "Mean Girls"?)
    - Different interrogators CANNOT be synchronous for this to work
        - Randomly staggered PRFs make sure it doesn't happen

Features - Sidelobe Suppression

- **Let's look at the antenna pattern again** (*repeated next slide*)
  - Notice the green main antenna pattern has high gain only over a narrow angle
  - Notice the little "bumps" of lower but finite gain – sidelobes
  - If a plane is close enough, it may be picked up on a sidelobe …. at the wrong angle!
  - Observe that the red auxiliary antenna pattern exceeds the green main pattern everywhere except the main lobe; It especially covers the sidelobes.
- **Interrogator (uplink) sidelobe suppression (ISLS)**
  - Remember I said there are two interrogation pulses? I lied.
  - A second transmitter sends a third pulse to the auxiliary antenna
  - Transponder only accepts signals stronger than this pulse
  - Thus, only signals coming in the main lobe are processed
  - This technique eliminates loads of unnecessary FRUIT
  - Not using ISLS is considered so selfish it is now illegal

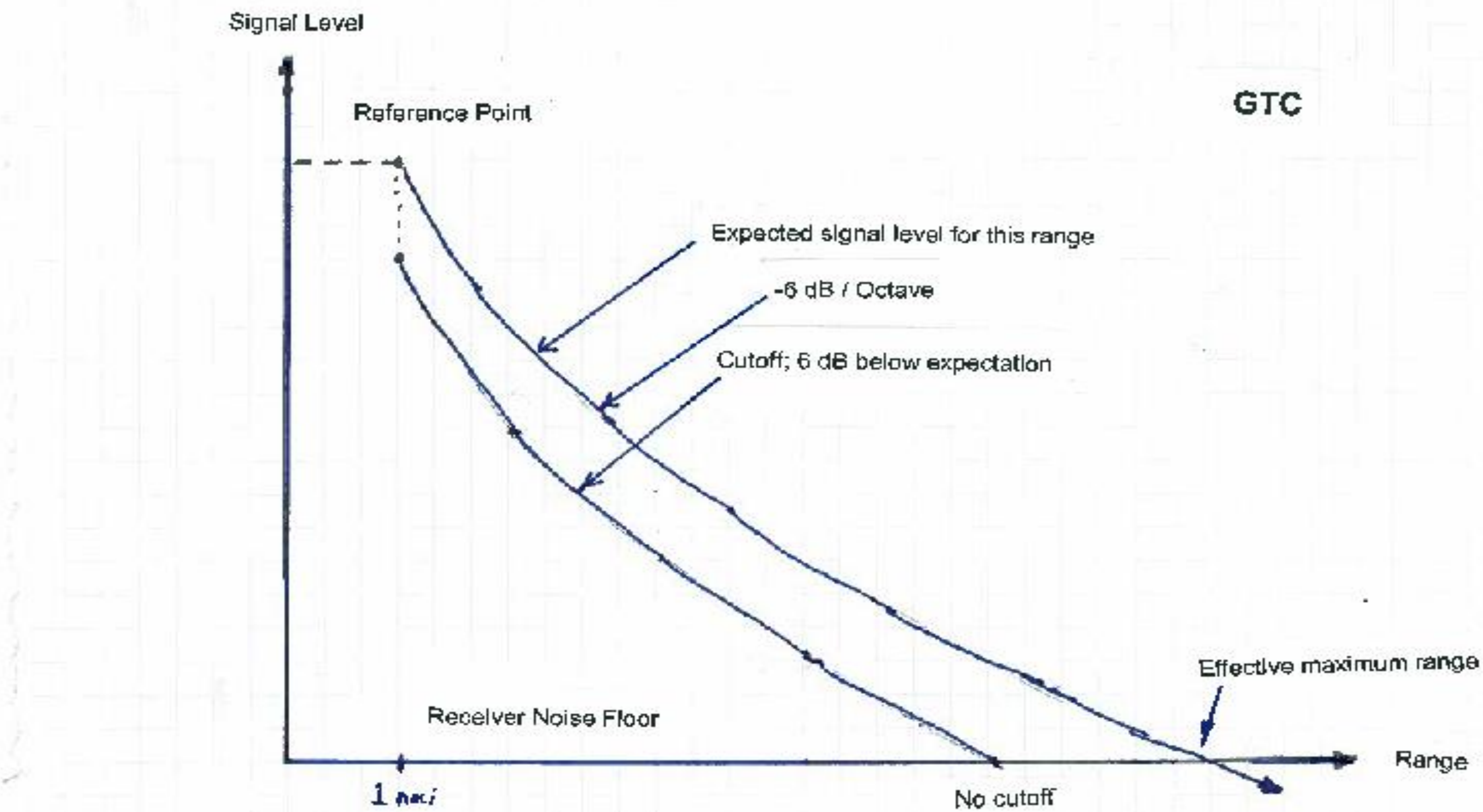
Representative IFF Antenna Pattern



More Features – RSLS and GTC

- **Receiver Sidelobe suppression (RSLS)**
  - Same idea as ISLS, but on the downlink side
  - We need a second receiver on the auxiliary antenna
  - So, which antenna is picking up the stronger signal?
  - If it is the auxiliary antenna, ignore the response.
  - Eliminates more FRUIT, clutter and junk
- **Gain – Time Constant (GTC)** (*curve next slide*)
  - IFF is a cooperative system with all parameters constant.
  - We can predict signal strength vs. range pretty closely
  - Signal drops at a predictable -6dB for every doubling of distance
  - (Radar guys – Eat your heart out!)
  - We allow a few dB margin; Anything less is dropped
  - We eliminate still more junk from further processing.

GTC Curve


Signal Level
Referance Point
GTC
Expected signal level for this range
-6 dB / Octave
Cutoff; 6 dB below expectation
Effective maximum range
Receiver Noise Floor
Range
1
No cutoff

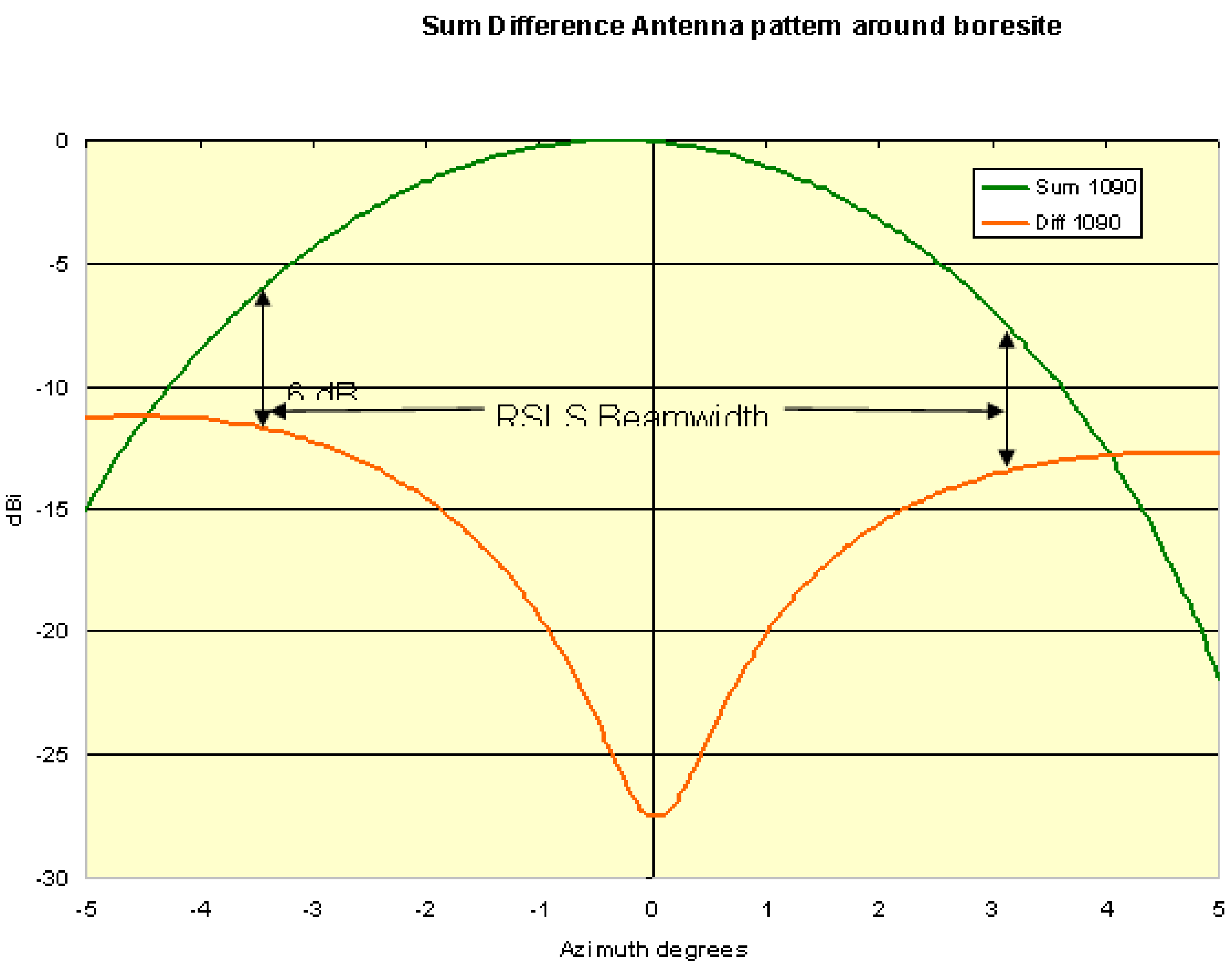
Azimuth (bearing) – legacy determination

- **The antenna beam can be up to 10 degrees wide**
  - We need to know target direction more precisely than that
  - There are two techniques for getting the beam center; Processing selects the best one for each target on each antenna scan
- **Legacy Beamsplit Azimuth**
  - Rugged, reliable and fairly accurate
  - See antenna position where the target first appears
  - See antenna position where the target disappears
  - Split the difference

Newer Monopulse Azimuth

- **We also use the auxiliary antenna and receiver for monopulse azimuth**
  - Look at the center of the antenna pattern again.
  - *(See expanded view on the next slide)*
  - Note that the auxiliary pattern nulls where the main lobe peaks
  - Note that the pattern is symmetrical around main beam center
- **SUM and DIFFERENCE monopulse channels**
  - The main antenna is the SUM channel; aux is the DIFF channel
  - These antenna patterns are stored in the IFF processor as "OBA tables"
  - If the SUM signal is, say, 10.3 dB above the DIFF signal, the OBA table tells us the offset from beam center (boresight) is, say, 2.55 degrees
  - The DIFF channel signals flip phase on different sides of the null; Used to determine whether it is 2.55 degrees CW or CCW from boresight
  - Even one reply will yield an azimuth (We usually average all we get)
  - This is very accurate for strong signals
    - With weak (long-range) signals, the null becomes noisy
  - The better of the two (beamsplit or monopulse) resulting from each beampass on a target is used.

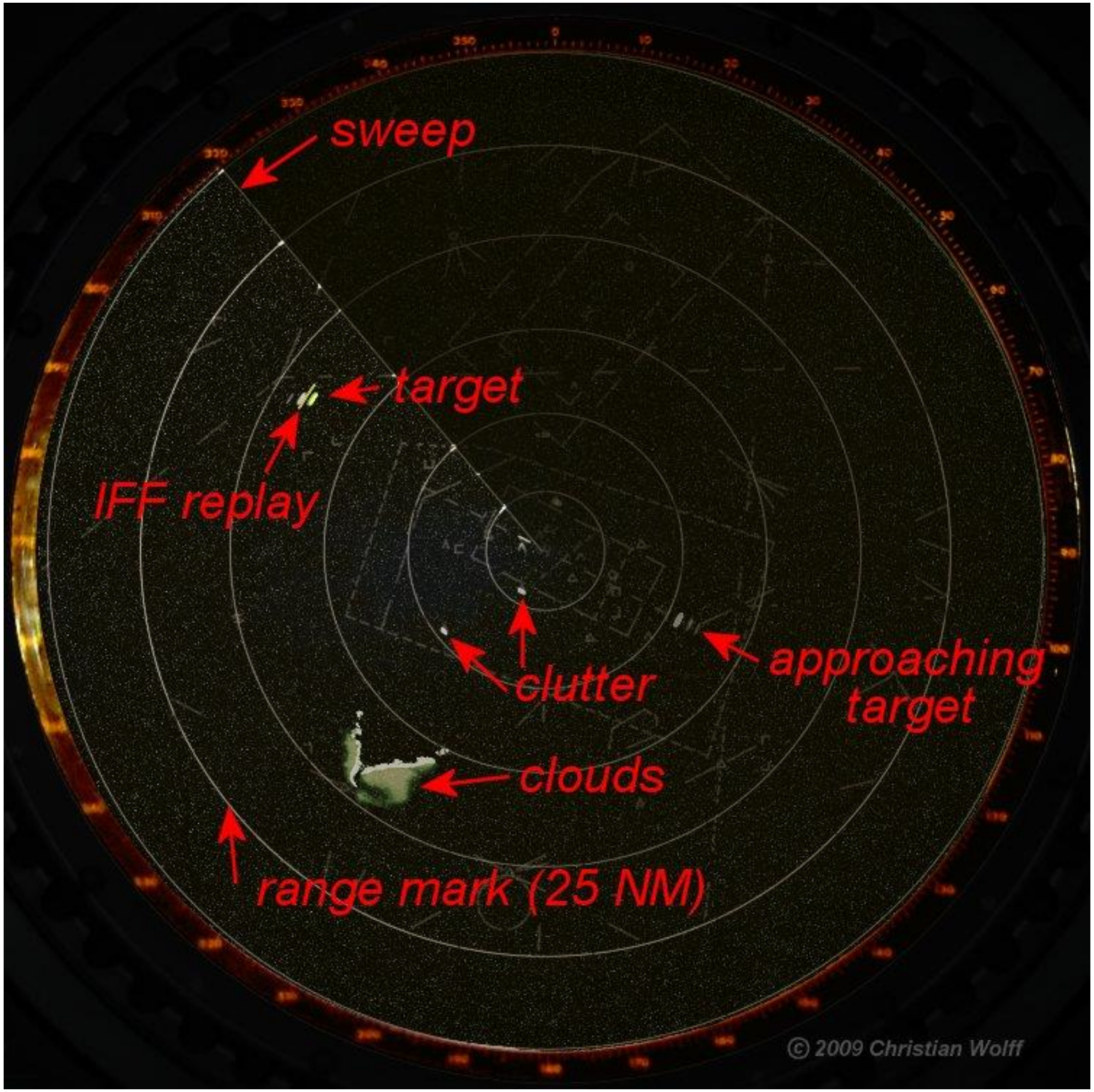
Monopulse antenna pattern



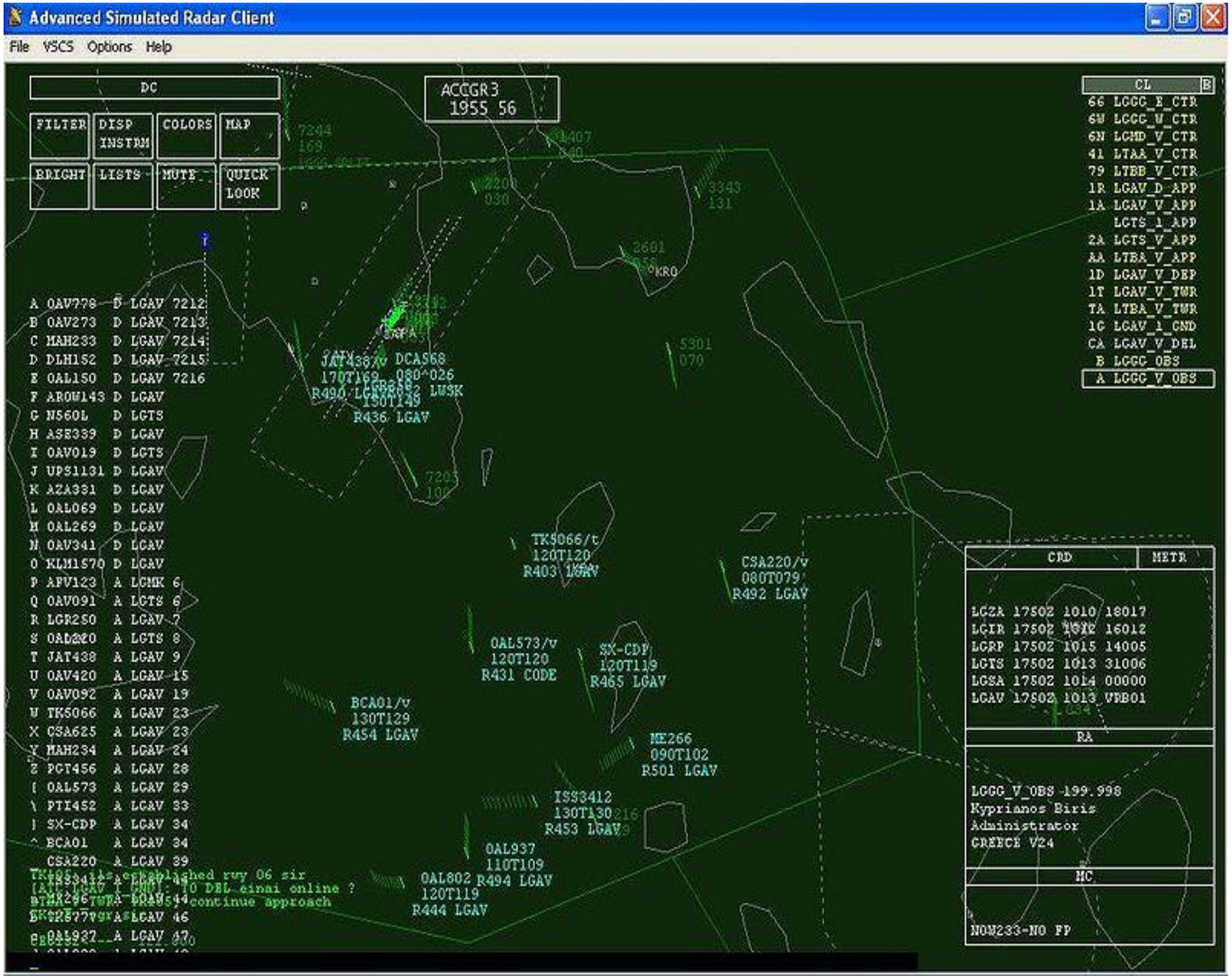
IFF signals sent to the displays

- **Raw (“code”) video**
  - Receiver detected output with no computer processing
  - In the beginning, this was all you had to work with
  - The next slide repeats the old radar display
  - Note the arcs (“bananas”) represent the antenna main lobe
  - It is crude compared to what we are used to seeing
  - But when things get ugly, it can be a godsend
- **Target Reports**
  - Computer processing determines what is a real target
  - The range, azimuth, and code are forwarded to the displays
  - The displays generate symbology over the code video that is useful to the operator (usually airline, flight number and altitude)
  - Computers in modern displays determine velocity vectors and add additional symbology to assist the operator
  - Two slides down shows typical modern display symbology

Representative early Radar Display



Modern ATC display



Chapter 3: Military Command and Control (including mobile platforms); 1960 until today

Mobile Radar / IFF Platforms

- Only the military has airborne Command and Control

- Puts a Radar and IFF at altitude for a better view

- Prevents aircraft from flying behind terrain to avoid detection
    - Increases distance to the horizon for greater range
    - In short, you cannot “fly below the radar” anymore
    - Air Force ground-based radar planes have gone from the RC-121 super constellation (next slide) of the 1950s to today’s E-3A AWACS
    - Navy aircraft carrier based radar planes have similarly gone from the WF2 (“Willie Fudd”) of the 50’s to today’s E-2D Advanced Hawkeye (2 slides down)

1953 – RC-121 Radar Picket Plane

E-2D – Latest Airborne Early Warning & Control

IFF Mark XII - Military Modes 1, 2 and 4

- **Mode 1 and Mode 2**
  - Identical to Mode 3 in operation
  - Used as identification by military controllers. Usually relate to ship, squadron, etc
  - These are not seen by civil ATC interrogators
  - Military aircraft transiting civil airspace must be good citizens and also have a Mode 3 code assigned so ATC can see them
- **Mode 4**
  - Mode 4 is a true Friend identification system
  - Note “friend or foe” is a misnomer – Determines friend vs. unknown
  - It is an encrypted system using a code-of-the-day that never repeats itself (next slide)
  - Obviously the encryption is a big deal; The old cryptos were often carried by armed guards to planes. Today it is less dramatic.

How does Mode 4 work?

- **The good news is I can tell you a fair amount**

- **Mode 4 Interrogation signals in space**
    - A header group of 4 pulses define a Mode 4 interrogation
    - The header pulses are followed by 32 pre-defined slots where a pulse is a 1 and no pulse is a 0.
    - There are over 4 billion possible numbers that can be sent
    - No number is ever sent twice during the 24 hours the code is in use
- **Mode 4 Reply signals in space**
    - Series of 3 pulses; always in the same pattern
    - Transponder turn-around time is lengthened by 1 of 16 possible delays
    - Each code has an expected delay; The interrogator tests for a match (uses de-FRUITer circuits)
    - Enough matches declare a friend

Limitations of Mode 4

- **In the last 40 years Mode 4's weaknesses have been discovered. The good news is that we can now do something about them**

- **The cryptography is old**
  - Recent advances in cryptography put the coding algorithms at risk of being compromised
- **Which Friend?**
  - Knowing a plane is a friend is not enough … WHICH friend is it?
  - The only way to find out is to use unencrypted Modes, which can be exploited by an enemy
- **Possibility of enemy exploitation or denying access**
  - There are two frequencies used; They can be jammed
  - An enemy can try to bluff his way through by guessing the 1-of-16 reply
  - Enemies can re-send interrogations or replies to exploit, bluff or confuse

…and the biggest problem with Mode 4 is…

- **Pilots no longer have full confidence in Mode 4**
  - To play it safe, some pilots turn off their transponders when going into combat to make sure no one can use it against them.
- **The fratricide danger** (Fratricide - Latin for "killing your brother" - has replaced the oxymoronic term "friendly fire")
  - Sometimes a pilot forgets to turn his transponder back on when he is heading home
  - Now, there is an unknown aircraft heading your way out of enemy airspace
  - Things can get really nasty very quickly
- **Help is on the way with Mode 5**

Chapter 4: Military Command and Control for the 21st Century; Mark XIIA - Mode 5

Mode 5 changes the game

- **Latest NSA codes and encryption**
    - Modern cryptography is harder to break
    - New encryption and hardware make captured equipment of little use
    - Embedded (internal) crypto units (KGV-122)
- **New data transmission techniques**
    - Utilizes modern data packets and spread spectrum
    - Both interrogations and replies are fully encrypted
    - Unique aircraft identifiers (like VIN on a car) instead of arbitrary codes make bluffing harder
    - Aircraft altitude and position are included, fully encrypted
    - Even range (round trip time) is encrypted (How do they do that?)
    - Last-ditch anti fratricide protection overrides shutdown

    - **Mode 5 is a tremendous leap in security and capability over Mode 4**

Mode 5 features

- **Mode 5 signals in space**
  - Interrogations and replies both use the same MSK spread spectrum data packets using encryption
  - To stay within legacy IFF frequency band, only limited spectrum spreading is used
  - MSK data modulation requires addition of an I-Q receiver detector in addition to legacy logarithmic detectors)
- **Random-Reply-Delay encrypts range**
  - The transponder delays responses by a random and significant amount
  - The encrypted message includes the exact delay
  - The interrogator reconstitutes range after decoding, with reduced opportunities for exploitation
  - Legacy GTC does not work on Mode 5. However, once processing restores the correct range, additional processing can perform the Mode 5 GTC function and reject unsuitable replies.

Chapter 5: Extreme Makeover of the National Airspace: Mode S

Why Mode S?

- **With ever more interrogators simultaneously "turning and burning," the air traffic system risks overload. Can we instead limit ourselves to one interrogation per target per antenna pass?**

- **Can we get all the information we need with only one response?**
  - Mode S uses data packets sent with DPSK modulation
  - Replies include unique aircraft identification (like the VIN on a car); Many also include aircraft position.
  - Received aircraft ID, range and bearing are stored for future use
  - Tracker / scheduler keeps tabs on when it is time to interrogate each target
  - Also need an acquisition process to register new ones as they come into range.

Mode S basic operation: RollCalls

- **Tracker / Scheduler**
  - Once a target is known, its position is tracked such that as the antenna rotates, a RollCall interrogation is set up to go out when the antenna is pointing at the last known azimuth.
  - Multiple interrogations can be sent out in one batch if they are organized by expected range space the replies and avoid overlap
- **RollCalls and Lockout**
  - When the interrogator knows a target's unique identification and position, it is interrogated when the antenna points at it
  - The interrogator also has its own identifier code; A successful interrogation locks out that interrogator's future acquisition attempts

Mode S Acquisition

- **Primary Acquisiton Method; Gotta catch 'em all**
  - In addition to targeted RollCalls, the interrogator sends out some AllCalls that invite untracked (no lockout) targets to respond
  - Targets already being tracked and RollCalled know the interrogator identification, and being locked out, they ignore acquisition requests from that particular interrogator.
  - A newly arrived aircraft will respond with its unique identification and position
  - The new aircraft is entered into the tracker and RollCalled with lockout to keep it from responding to more AllCalls
  - When an interrogator is first turned on, it sends out a code to have only a random fraction of new transponders respond. This holds down everyone responding at once, but at a cost of needing several antenna scans to catch 'em all.
  - Just in case something goes wrong, lockouts time out after 18 seconds without a RollCall, so acquisition can resume.

Ground-Based Mode S Air Traffic Control

- **Mode S is extensively used today in Europe**
  - Very limited use today in the United States

- **Military aircraft transiting Mode S controlled airspace**
  - Mode S is a civil system. While it shares the use of data packets with Mode 5, none of the security features apply
  - Military targets must continue to be good citizens transiting civil airspace and respond to Mode S interrogations.
  - Keep in mind that Mode S is on military aircraft is SOLELY for transiting civil airspace. In military situations, a system that periodically and openly broadcasts one's GPS coordinates to all is a really terrible idea

  - **ADS-B Squitters**
  - Mode S transponders broadcast unsolicited transmissions several times per second, including the aircraft ID and its position.
  - These broadcasts are called "squitters"
  - Squitters are useful for collision avoidance systems, etc.

Mobile Mode S Platforms (E-2D, AWACS)

- **Mode S from a moving platform … Another fine mess you got us into, Ollie**
  - Unlike aircraft identifiers, Mode S never allocated interrogator codes for visitors (“jes’ passin’ thru, ma’am”), so there aren’t enough to go around.
  - Current philosophy is that all mobile platforms share one common identifier.
  - If two interrogators with the same code are nearby, the first one to acquire a new target locks it out, thus making it invisible to the second interrogator. That is unacceptable.
  - We can turn off lockout on our interrogations, but then every AllCall causes pandemonium. Now what?
  - We have come up with some ideas; None are elegant.

Mode S Mobile Acquisition

- **Acquisition via Squitter** (non-proprietary idea)
  - All it takes is one squitter to give us what we need to start RollCalling a target (unique ID and location)
  - However, our antenna beam is too narrow and moves too fast; It slips between most of the squitters.
  - It can take quite a few antenna scans to catch 'em all
  - If an E-2D is set to passively receive and store squitter information while travelling out to station, upon arrival it should have almost all the targets pre-loaded in the tracker.

  - **There are other, proprietary, approaches, but not much better.**

FAA discomfort with Mobile Mode S

- **The FAA is fighting flight testing mobile Mode S**
  - You must acknowledge that the FAA is responsible for millions of lives every day. They simply cannot make a mistake
  - They wear their paranoia like a uniform
  - Things were working pretty well … until we came along
  - Besides, even normally, getting authorizations in glacial
  - Remember, the US has not committed to Mode S yet even for ground stations
  - Military agencies are in a constant battle with the FAA to get flight testing authorized

Chapter 6: New Collision-Avoidance Systems

Collision Avoidance

- **Mode S Passive Reception**
  - Many Mode S aircraft signals, both squitters and RollCall replies, contain their aircraft's GPS coordinates.
  - A receiver passively intercepts Mode S signals around it and compares the aircraft position to one's own GPS coordinates.
  - If another aircraft is deemed too close, an alarm is sent to notify the flight crew.
- **TCAS**
  - A small interrogator with a simple directional antenna (typically 4 vertical monopoles – a scheme used on some police cars for LoJack)
  - It provides low-power interrogations for a short range beam covering a wide azimuth
  - Aircraft close enough to decode the interrogations may be too close. Their responses will trigger an alarm with a general indication of direction.

Chapter 7: FAA NEXTGEN AIR TRAFFIC CONTROL (2020?)

FAA NEXTGEN next generation air traffic control system (2020)

- **Uses NO interrogators at all; Totally squitter based**
  - Since all aircraft will soon be squittering their position, interrogators are less important than before.
  - The NEXTGEN system is to solely receive squitters from all aircraft within range of air traffic control center.
  - A simple omnidirectional antenna would suffice for short range…
  - ….But, the high gain of today's antennas is needed for longer range coverage
  - The FAA proposes a compromise of 6 antennas, each one covering 1/6 of the sky
  - However, these antenna outputs cannot simply be combined (the background noise is combined too) so each antenna requires its own receiver and the 6 receiver outputs have to be properly processed
  - Scuttlebutt is that the notoriously late FAA is behind schedule on the stated year 2020 implementation
  - Appears we will still be using what we have for a while longer

END