The Past, Present and Future of Secondary Radar

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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 μS 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”)
  - Air Traffic Control Radar Beacon System
  - Overall FAA Civil Air Traffic Control

• **En-route Control Centers**
  - Maintain radar/IFF control of aircraft at altitude across the country

• **TRACON** (“tray-kon”)
  - Terminal Radar Approach Control
  - 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 – RSL and GTC

• **Receiver Sidelobe suppression (RSL)**
  • 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

- Expected signal level for this range
- Cutoff: 6 dB below expectation
- Effective maximum range

Signal Level

Reference Point

Receiver Noise Floor

No cutoff

Range
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

Sum Difference Antenna pattern around boresite

Azimuth degrees

dBi

APR

RSI S Beamwidth
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 XllIA - 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 Acquisition 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