5.3 *Examples of systems*

1. Examples
2. *Klein Heidelberg*
3. Bistatic SAR
4. Air Defence
5. Maritime
6. Through-wall detection
7. GRAVES/LOFAR
8. Equivalence with MIMO Radar

Examples of bistatic radar systems

- *The idea of bistatic radar, as with similar techniques of marginal value, is resurrected on a regular basis, but usually goes away after careful examination.*
- *It might very well be used for special purposes, but it is not likely to be widely deployed in the near future.*

M. I. Skolnik

Chapter 5, *Countermeasures Handbook for Aircraft Survivability,* February 1977

Examples of bistatic radar systems

- forward scatter fences
- *Klein Heidelberg*
- SPASUR
- early PBR
- *Silent Sentry*; *Homeland Alerter*
- Manastash Ridge Radar
- cellphone basestation-based PBR
- HF PBR
- bistatic SAR

The Daventry Experiment: 26 February 1935

The BBC Empire transmitter at Daventry gave a beam 30˚ azimuth × 10˚ elevation at 49 m wavelength, and the beat note from a Heyford bomber at a range of 8 miles was clearly detected.

Painting by Roy Huxley

Forward scatter fences

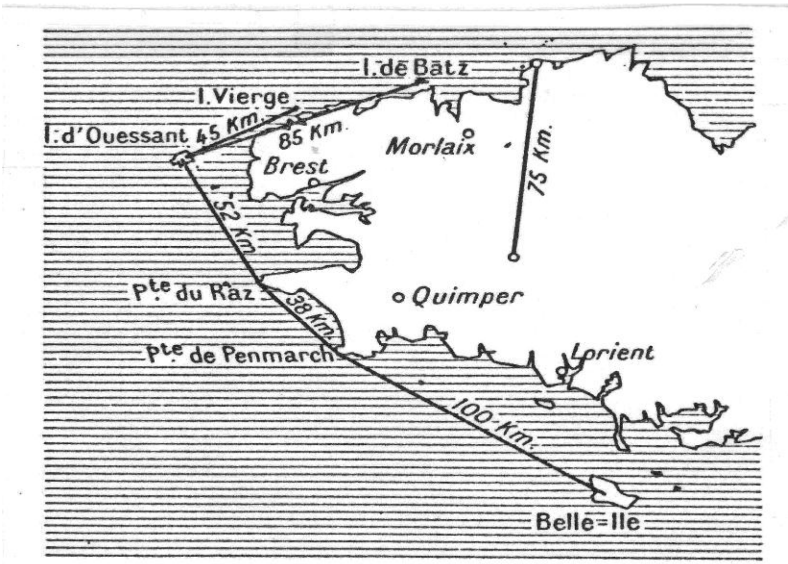
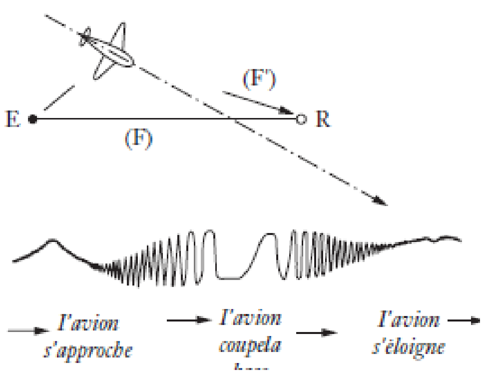


Fig. 1. — « Barrages électromagnétiques » protégeant Brest en 1939

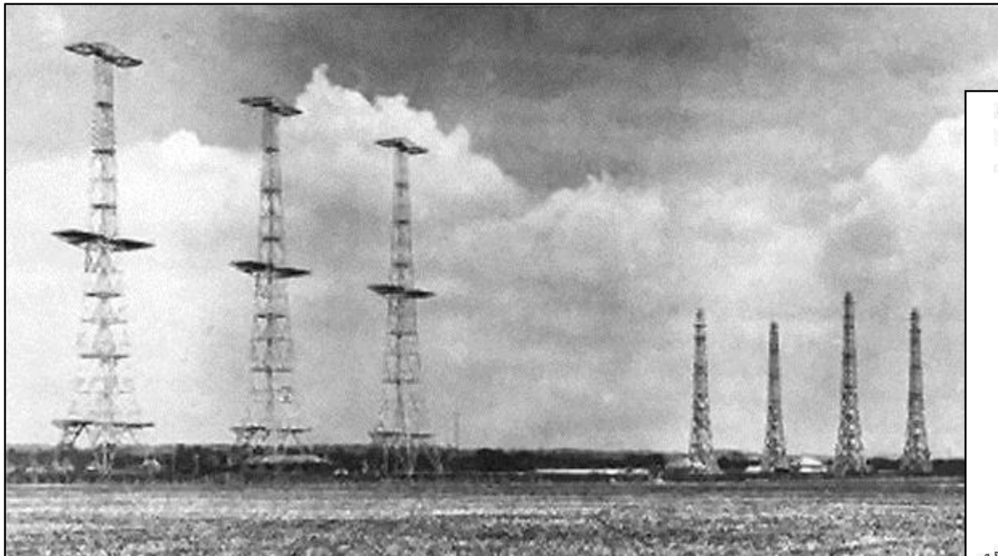


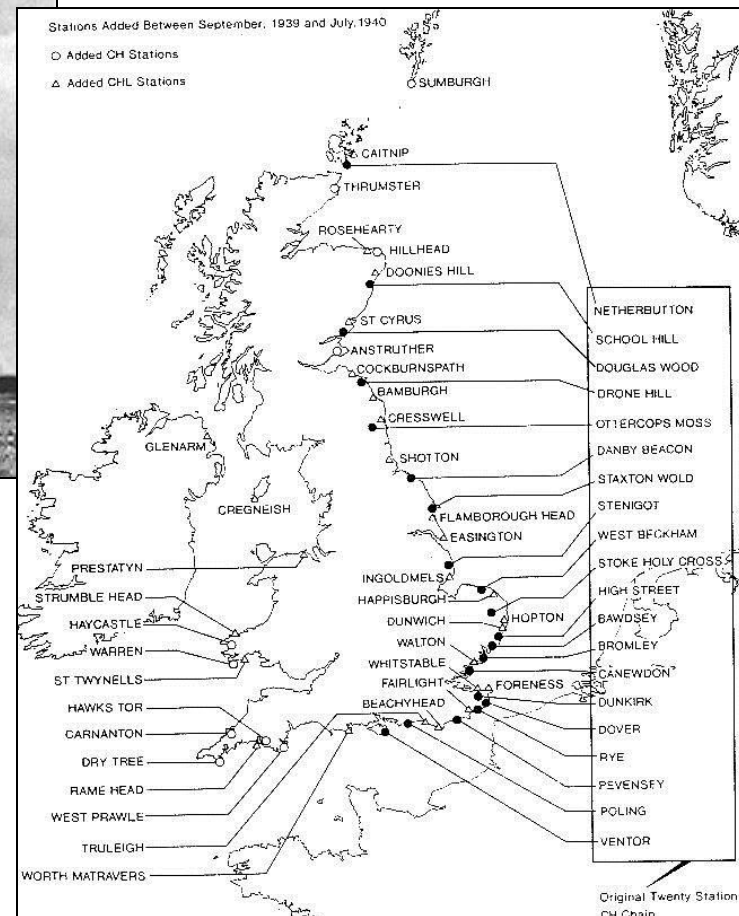
Six of Pierre David's 30 MHz radar fences deployed around Brest in 1939.

It is not clear why two gaps remained. Note the near parallel fences in the northwest coverage, which suggest partial elements of his more complex configuration called the *maille en Z*. It could generate course and speed estimates for non-maneuvering aircraft.

Pierre David, *Le Radar*, PUK Coll. Que sais-je? No. 381, 1969.

CHAIN HOME





Neale, B.T., ‘CH – the First Operational Radar’, *GEC Journal of Research*, Vol. 3 No.2 pp73-83, 1985.

SPASUR 1 MW-CW TRANSMIT ARRAY

Doppler tracking; angle-only measurement; multistatic for isolation

Courtesy eyeball-series.org

The U.S. Naval Space Command Space Surveillance System uses two-mile-long antennas at three transmitting and six receiving stations to detect virtually any earth-orbiting satellite coming within the 216.97MHz–216.99MHz transmitters' illuminated fields. This is a one-mile section of a SPASUR transmitting antenna at the Lake Kickapoo Field Station, 30 miles southwest of Wichita Falls, TX. *Photo courtesy of the U.S. Naval Space Command.*

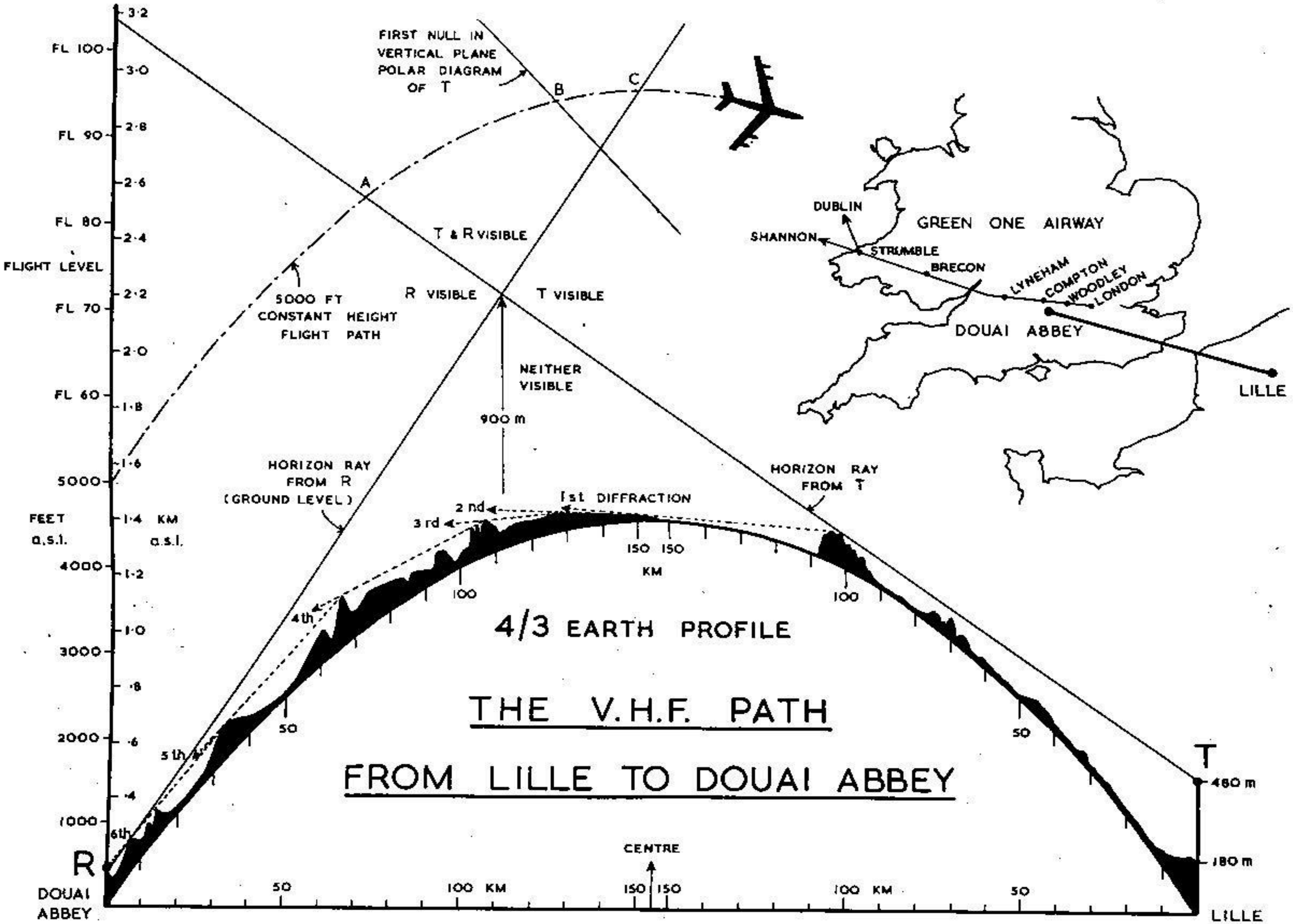


Fig. 1. The v.h.f. path from Lille to Douai Abbey. The curvature of the earth is drawn at 4/3 times its actual radius to allow for the normal effect of the atmosphere in bending v.h.f. signals. The inset map shows the radio path and the reporting points along the "Green One" airway which will be mentioned in Part II of the article. The detail of the diagram is discussed in the text.

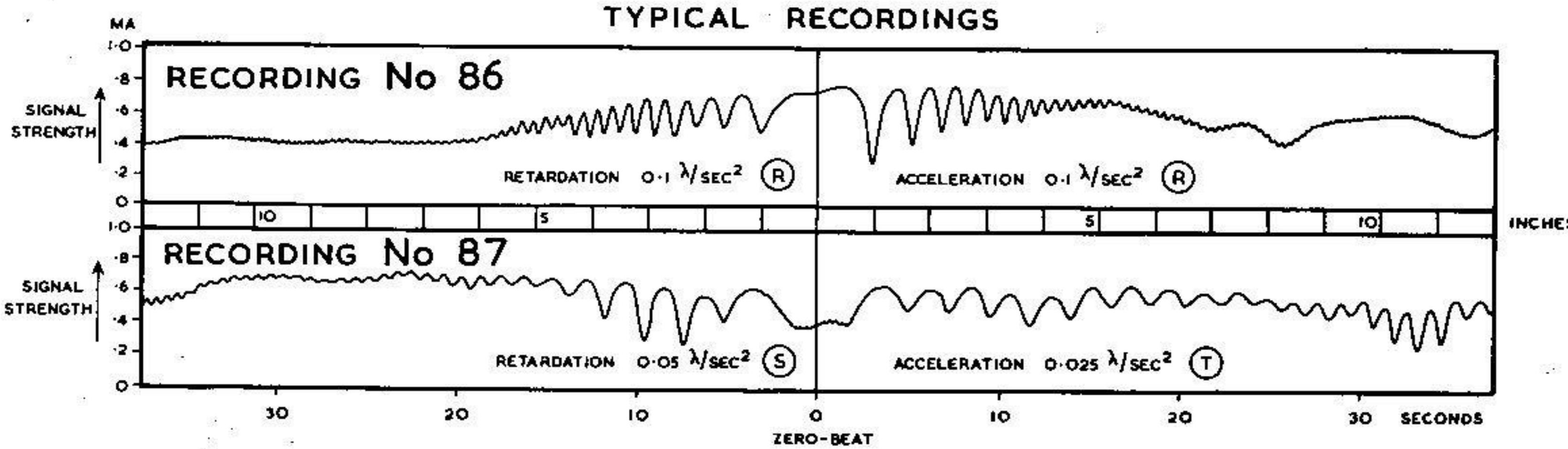


Fig. 2. Two typical recordings of "steam train" fading. The train halts briefly at the station where the variable frequency ripple passes through zero-beat. Each minimum in signal strength causes a surge of background noise in the receiver which sounds like the "chuff-chuff" of a steam train.

V.H.F. FADING OBSERVATIONS LILLE — DOUAI ABBEY

174·1 MCS

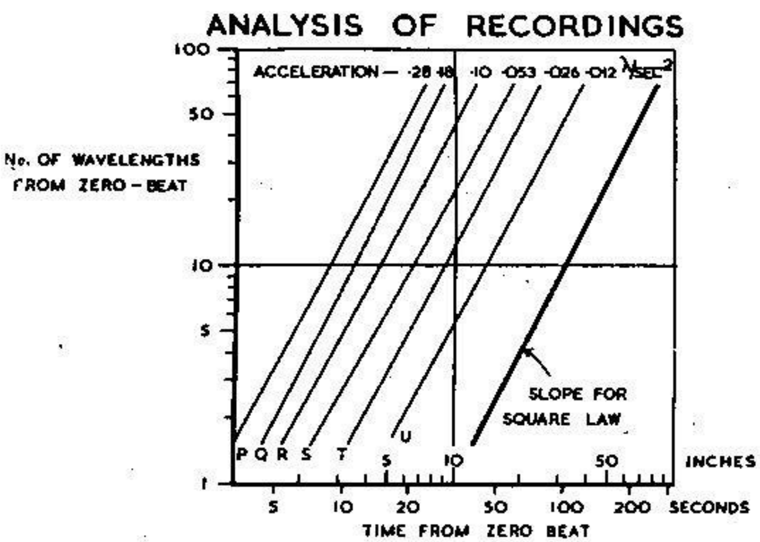


Fig. 3. An analysis of a large number of recordings of steam train fading. Each line P Q R S T U is representative of many recordings. All are seen to have a slope very nearly that of a "square law."

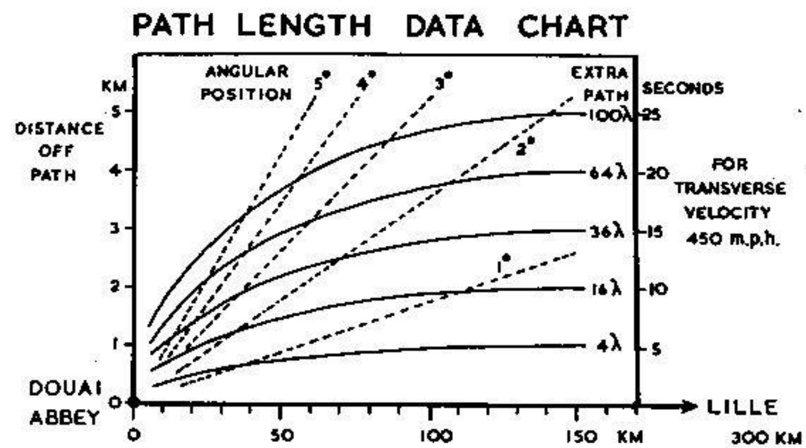
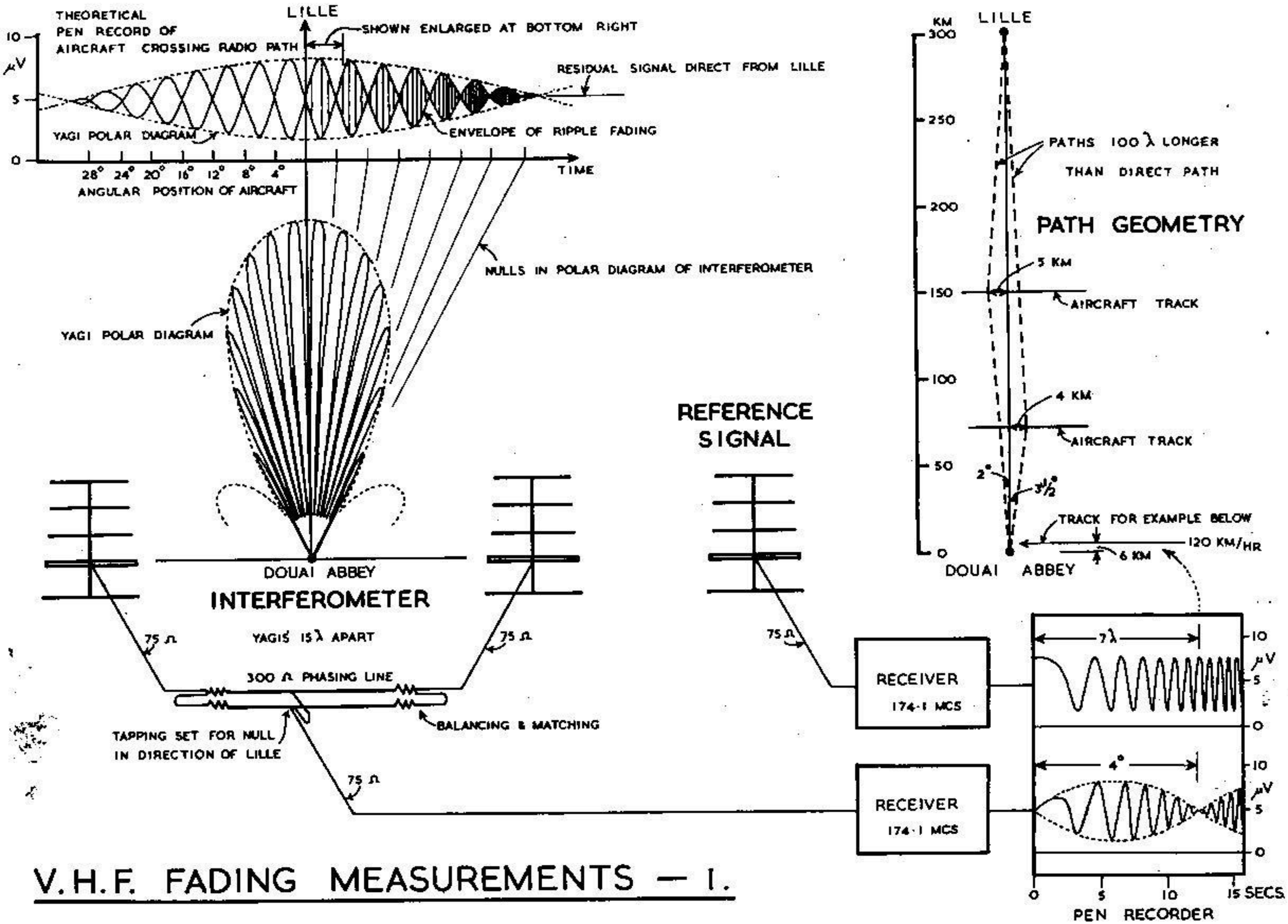


Fig. 4. Path length data chart showing how the length of the bounce-path increases as an aircraft moves off the direct path between Lille and Douai Abbey. The straight lines show the angular position of the aircraft from the receiver relative to the direction of Lille.



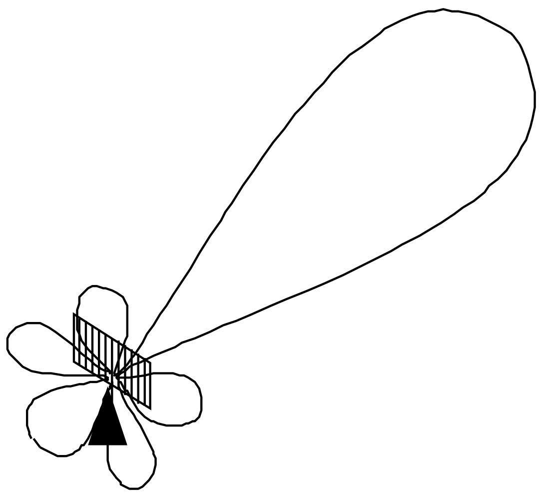
V.H.F. FADING MEASUREMENTS — I.

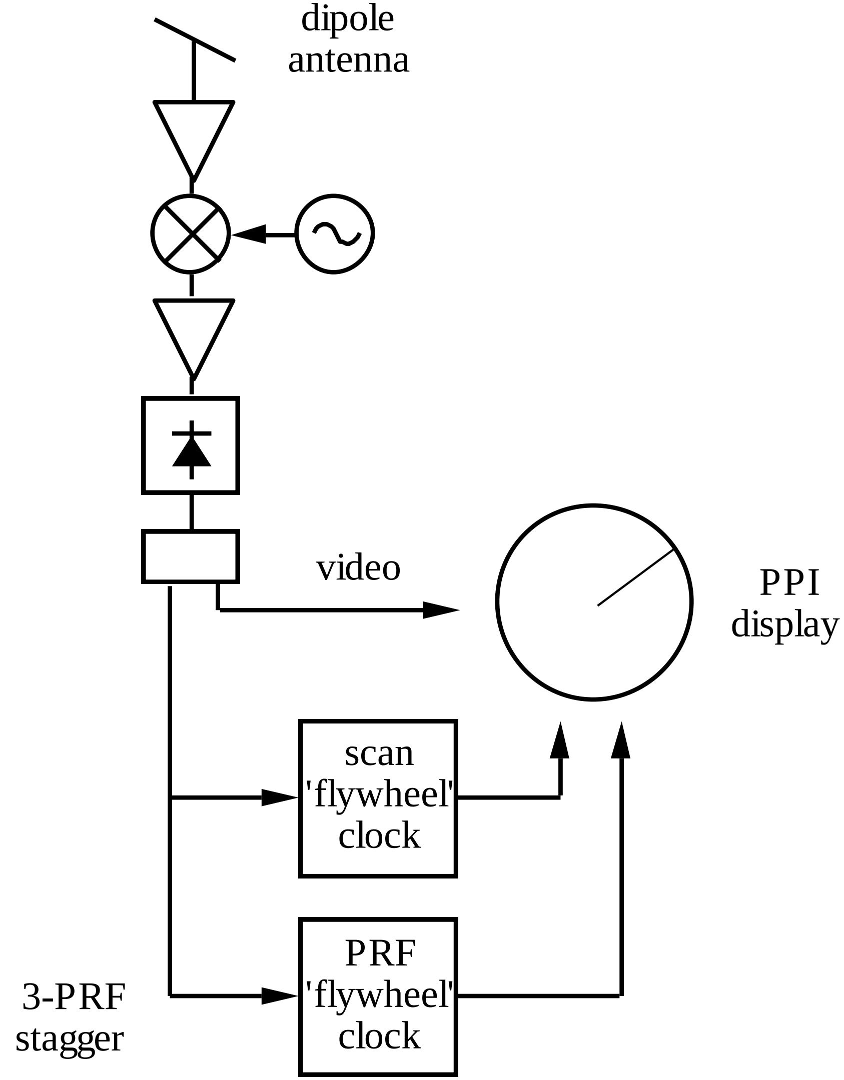
Fig. 1. The arrangement for the first experiment to find the position of an aircraft causing a particular steam train fade. All the details are discussed in the text. The two Yagis of the interferometer were at a height of 10 wavelengths, 55 ft.

SANCTUARY

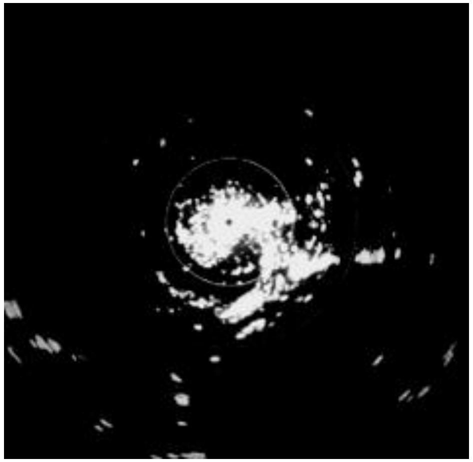
Fawcette, J. ‘Vulnerable radars seek a safe sanctuary’, *Microwave Systems News*, April 1980, pp45-50.

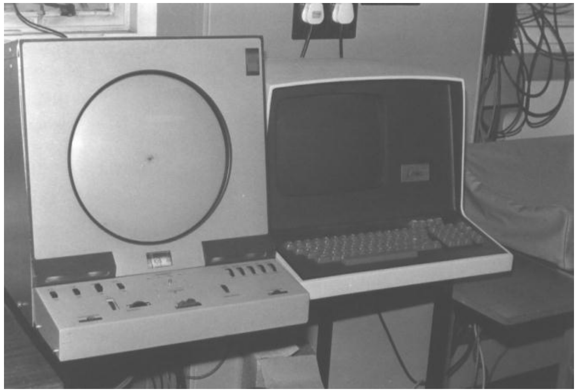
Early bistatic radar experiments at UCL

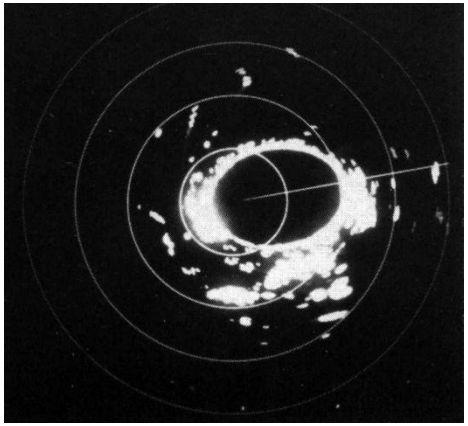




Early bistatic radar experiments at UCL



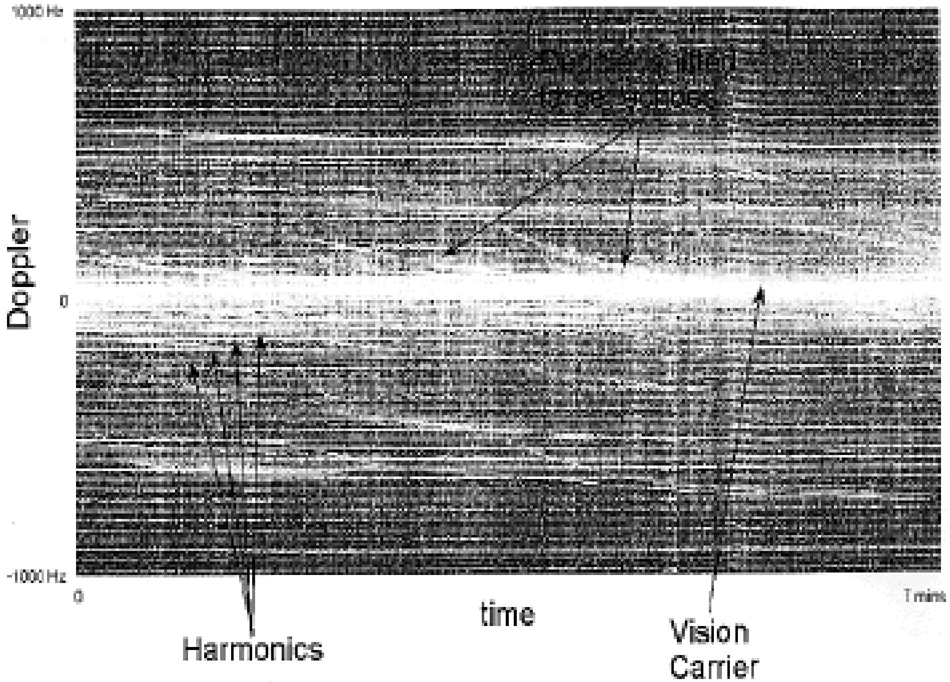


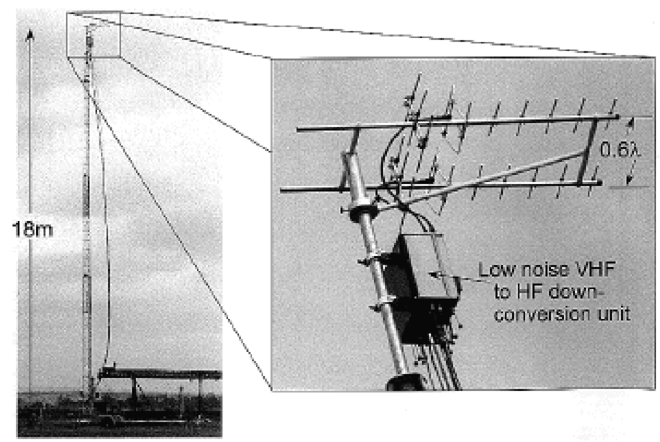


Schoenenberger, J.G. and Forrest, J.R., ‘Principles of independent receivers for use with co-operative radar transmitters’, *The Radio and Electronic Engineer*, Vol.52, No.2, pp93-101, February 1982.

Griffiths, H.D. and Carter, S.M., ‘Provision of moving target indication in an independent bistatic radar receiver’; *The Radio and Electronic Engineer*, Vol.54, No.7/8, pp336-342, July/August 1984 .

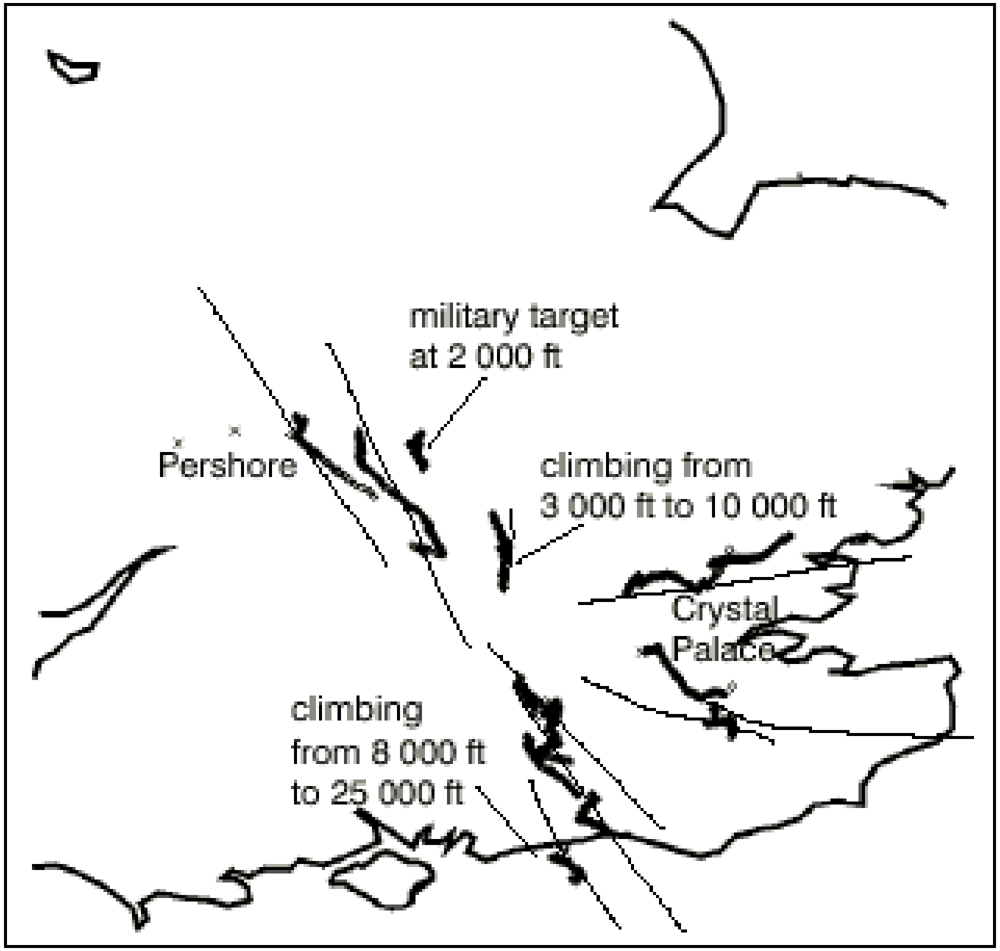
Target tracking using television-based bistatic radar





Howland, P.E., ‘Target tracking using television-based bistatic radar’, *IEE Proc. Radar, Sonar & Navigation*, Vol.146, No.3, June 1999.

Target tracking using television-based bistatic radar



Howland, P.E., 'Target tracking using television-based bistatic radar', *IEE Proc. Radar, Sonar & Navigation*, Vol.146, No.3, June 1999.

LOCKHEED MARTIN

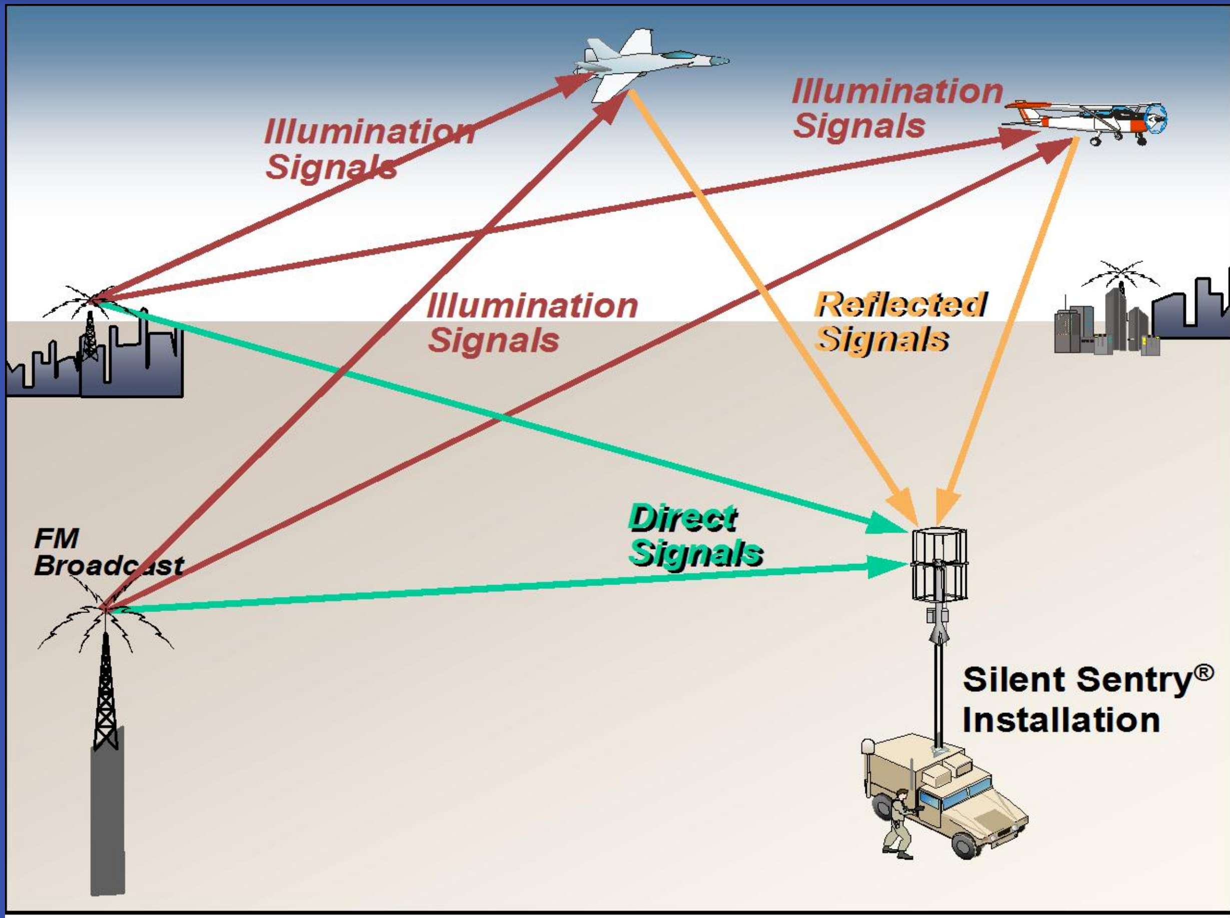
Mission Systems

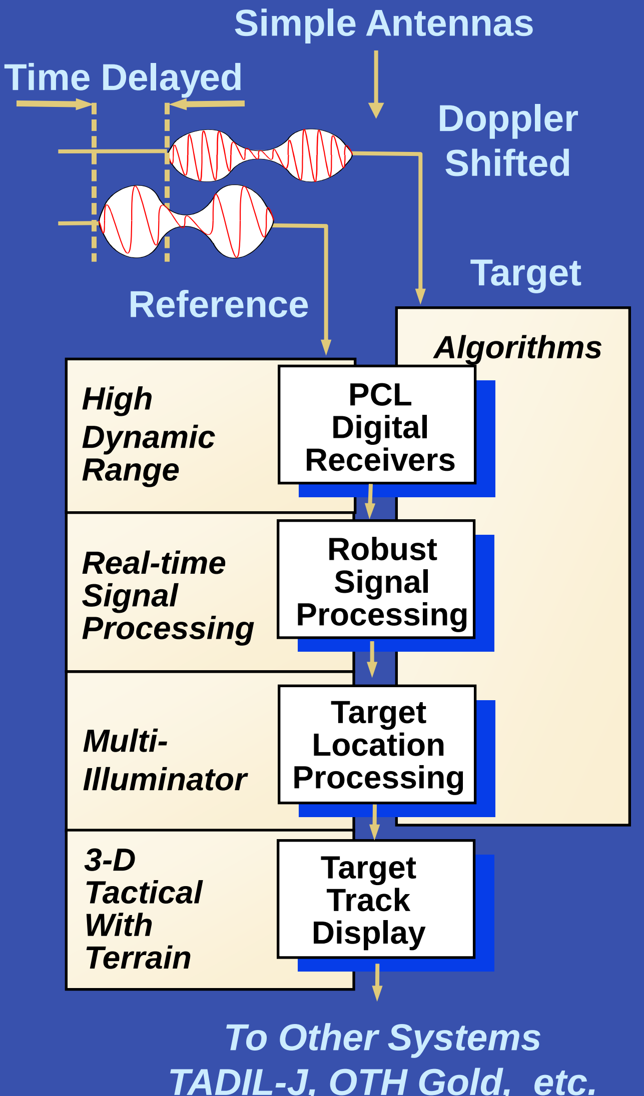
Silent Sentry®
Passive Surveillance System

26 June 2003

® Silent Sentry is a Registered Trademark of the Lockheed Martin Corporation.

Passive Coherent Location
Principles of Operation





RF Energy in the Environment is Reflected from a Target and then Collected and Compared to the Original Signal to Provide Detection and Tracking Information

Silent Sentry Overview

Silent Sentry's Passive Coherent Location (PCL) technologies enable cost-effective, all-weather, persistent passive detection and tracking for air surveillance and missile targets.

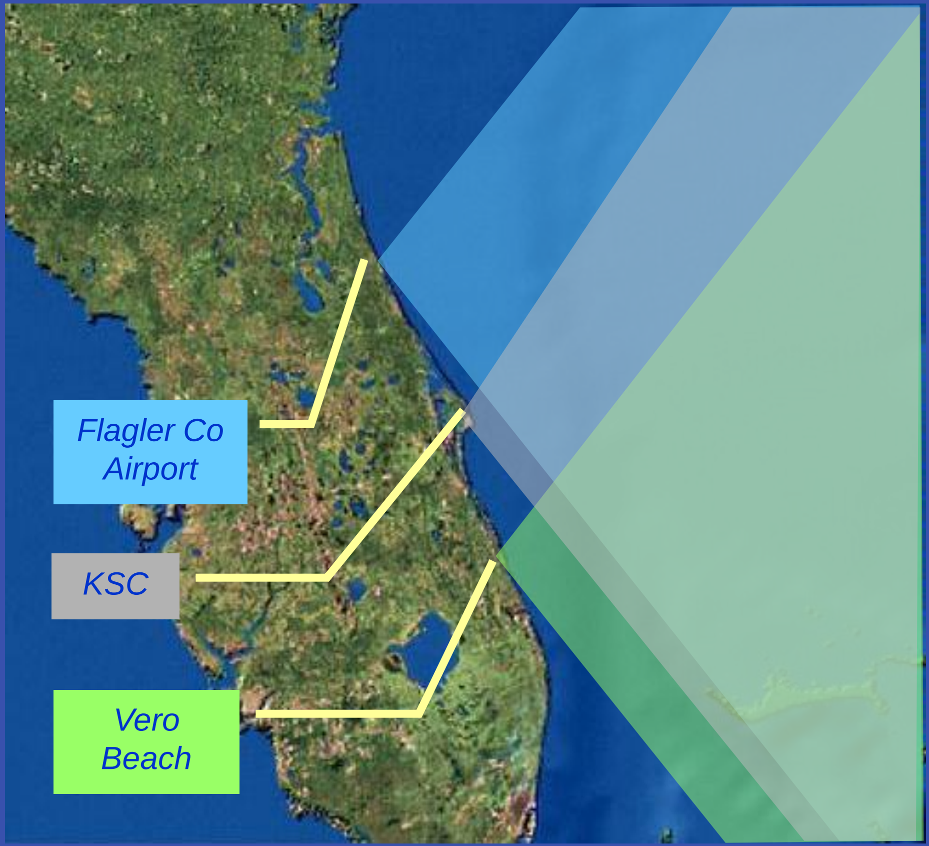
Recent Test Results

Operational
<u>Application</u>

Missiles → NASA Real-time Networked SLV Tracking → **Launch/Landing Range Safety**

Air → GAPS Single-Node Air Surveillance Tests → NASA Networked Air Surveillance Demonstration → **Air Surveillance**

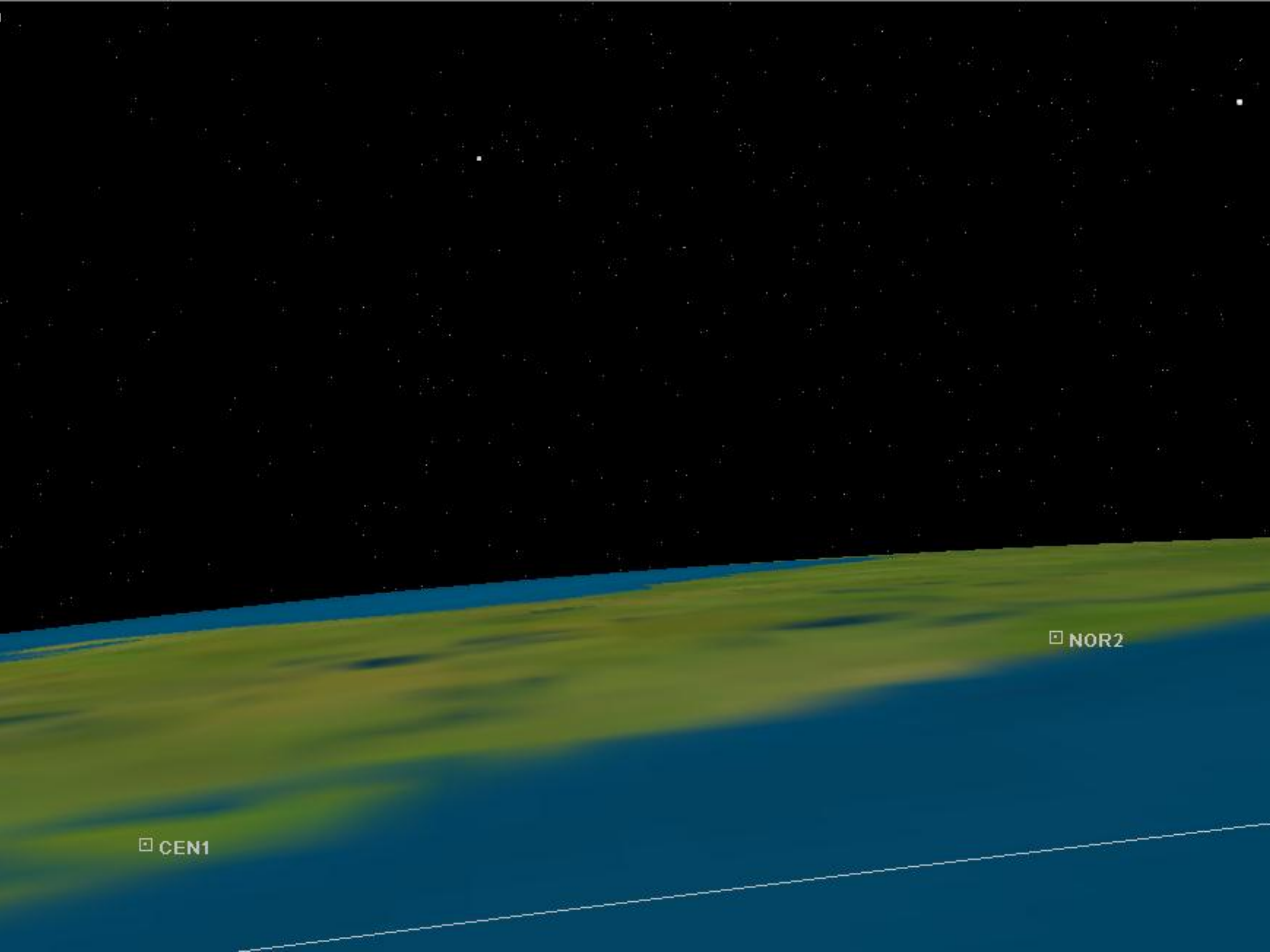
NASA Phase 2.3, Fall 2002



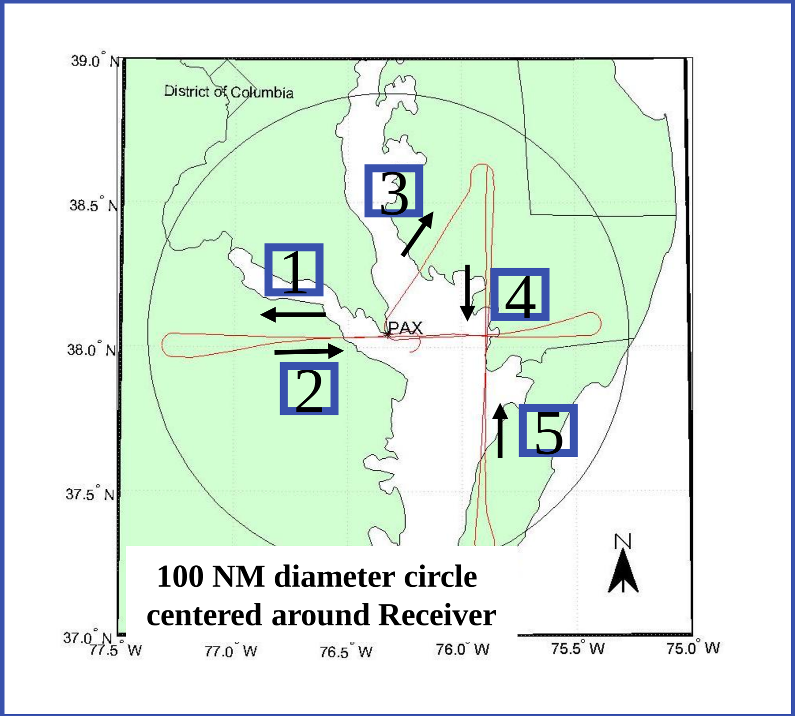
- STS-113
- Delta IV
- Atlas 2A

- Real-time Networked Operation of 3 Silent Sentry Nodes
- Space Launch Vehicle Tracking

Historical Event – First EVER Real-Time, 3-D Space Launch Vehicle Tracking using Indigenous FM Illuminators


NOR2
CEN1

GAPS ACTD Tests, June 2002

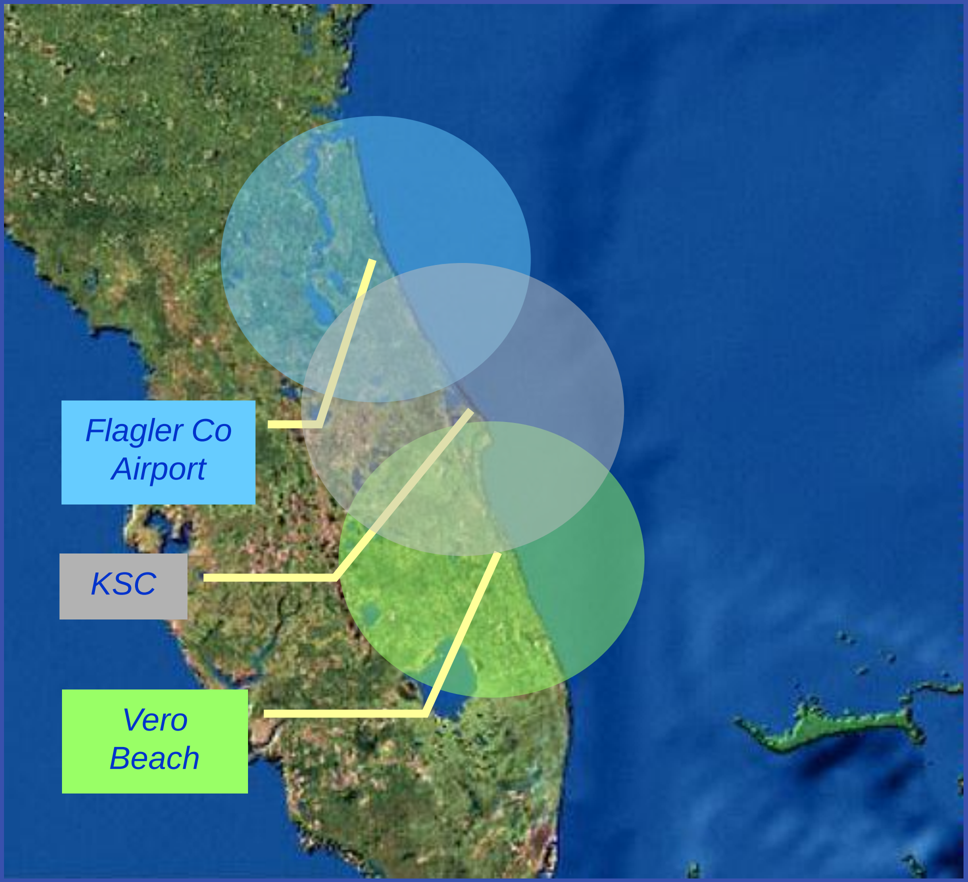


Cooperative Target:

Cheyenne 2

Real-time tracking results: 160m horizontal, ~725m vertical position errors

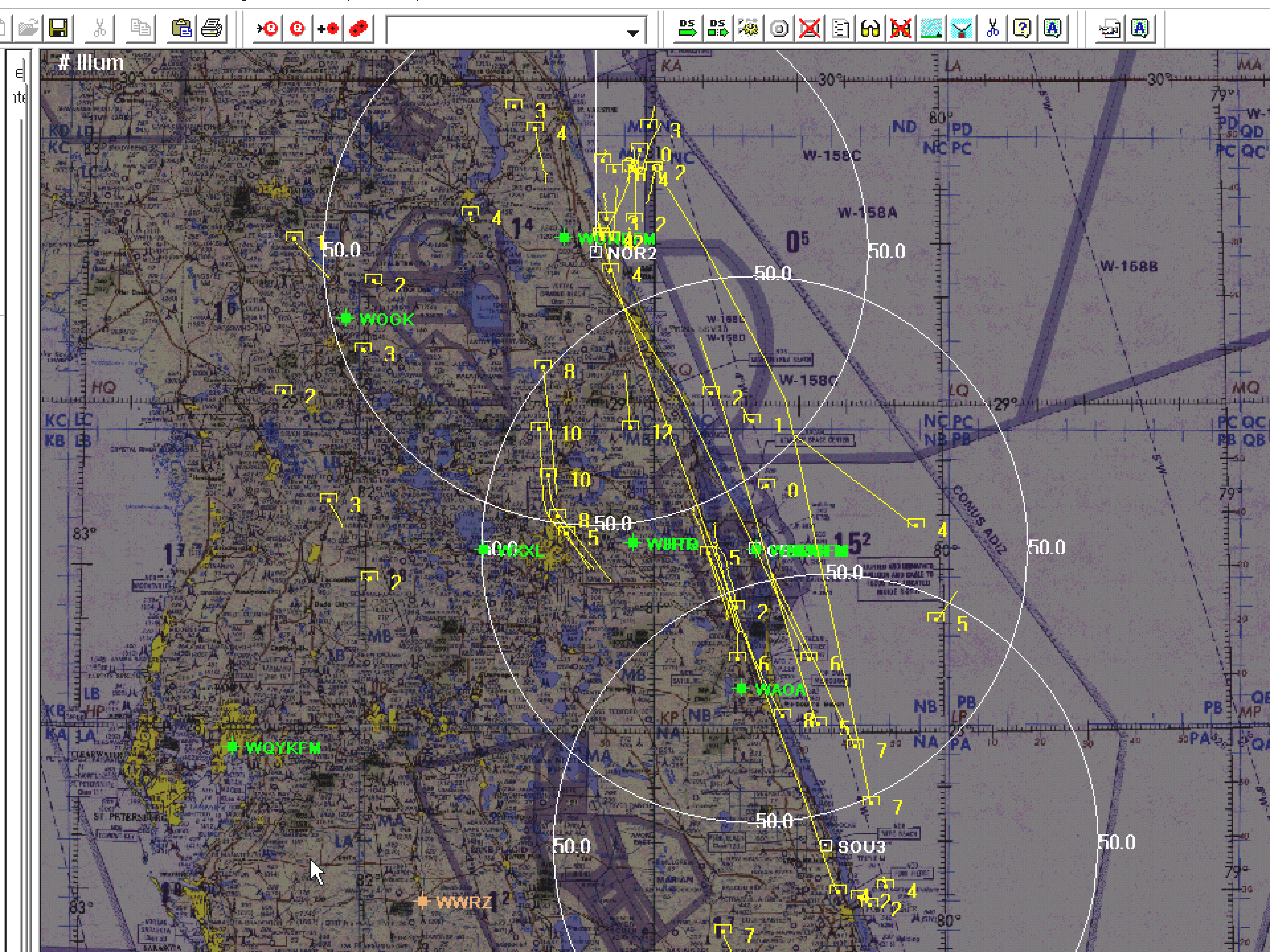
Integrated Real-time Regional Air Picture From a 3-node System



November 16, 2002

- Real-time networked operation installed for NASA Space Launch Vehicle tracking
- Three SS-3 nodes using 360° antennas for network testing
- Medium to high altitude aircraft tracking
- Data-level (not track-level) fusion @ KSC master node
- T1 speed commercial lines between slaves and master nodes

Real-time Tracking of Multiple Air Targets over Extended Area



Illum
W-158C
W-158A
W-158B
NOR2
WOGK
WAOA
WQYKFM
WWRZ
SOU3
CONUS ADIZ
50.0

Product Specifications

Performance

Surveillance Volume
- Azimuth: Up to 360°
- Elevation: 60°
- Continuous Search

Range
- 50 to 100 nmi within FOV

Targets
- 100+ simultaneously
- Aircraft and missiles

Accuracy
- 100-200 m horizontal position
- 1000 m vertical position
- <2 m/s horizontal velocity

Data Output
- SS track format or OTH Gold

Survivability

Operating Environment
- Room temperature
- Shelter protected
- 1.5 kw 120V power

Reliability
- Standard digital component based
- No moving parts

Precipitation
- All weather antenna
- Shelter protected equipment

Detectability
- Covert when operating with indigenous illumination

Transportability

Transport Speed
- Level highway: speed limit
- Cross country: 10-15mph

Transport Vehicle
- Shelterized HMMWV or SUV
- Enclosed truck/SUV

Grades and Road Conditions
- VME Rack
- Ideal for Road Transport
- Withstands moderate off-road conditions

Emplacement
- Less than 1 day
- 1-2 person setup

Mission Planning

- Silent Sentry isn't expected to be right for all locations and missions
- Successful deployments must consider:
  - Transmitter power, location, operation
  - Receiver location options / number of nodes
  - Terrain
  - Communications bandwidth available
  - Acceptability of cooperative transmitter augmentation when existing illumination has gaps

Mission Planning Is Key to Realizing Silent Sentry Strengths

Air Surveillance Strengths

Strength Area	Mission Improvement	Additional Improvement Possibilities
Flexibility of System Design The SS3 architecture easily supports various antennas, transmitters, continued Moore's law improvements, etc	**Reduced Life Cycle Costs** Costs to deploy and maintain SS3 continue to drop while additional performance can be added	Various practical extensions identified: smaller footprint, HF/TV transmitters, automated illumination selection…
Environmentally Acceptable , Passive Deployment PCL can be widely deployed with minimum impact , thus mitigating environmental concerns. It does not radiate, consumes little power, and is relatively small and lightweight.	**Ease of Deployment** Systems can be deployed without thought to radiation issues, simplifying planning.	Use existing infrastructure; unmanned/remote operation features…
Tracking of Low, Slow, Non-cooperative Targets 3-D tracking with high accuracy horizontal and velocity state vectors. Continuous total volume surveillance and high update rate.	**"Gap Filler" Below 5000' in Current Surveillance Architecture** Data output in OTH Gold, TADIL-J, or other standard format.	Low altitude and range coverage increases with additional Silent Sentry nodes or by mounting on cell towers.

Air Surveillance Potential Limitations

Issue	Probability of Occurrence	Impact of Occurrence	Mitigation Strategies
Transmitter Availability >3 geographically diverse TX's with sufficient power & operate 24/7	**Deployment Dependent** Most of USA are well covered, much of Asia, Europe, and Mid-East	**Potentially no track, or reduced accuracy**	**Options:** ▪ Network receivers (3 Rx / 1 Tx = 3 Tx / 1 Rx) ▪ Supplement w/ Cooperative TX's
Receiver Environment Office equipment environment, appropriate communications bandwidth for networked RX's	**Deployment Dependent** Office conditions and communications not everywhere	**Restricts deployment options**	**Options:** ▪ Militarize equipment ▪ Communicate tracks, not measurements to reduce bandwidth
Lack of Validation Testing System not tuned or tailored to representative scenarios	**Deployment Dependent** System detection and tracking performance varies with scenario	**Potentially restricted range or track breakage**	**Options:** ▪ Validation and tuning/tailoring program
Terrain Blockage Line-of-Sight required between target / Tx and target / Rx	**Deployment Dependent** Varies by topography	**Tracking won't occur until target LOS**	**Options:** ▪ Mount on mountain peaks, cell towers, aerostats ▪ Increase numbers of receivers

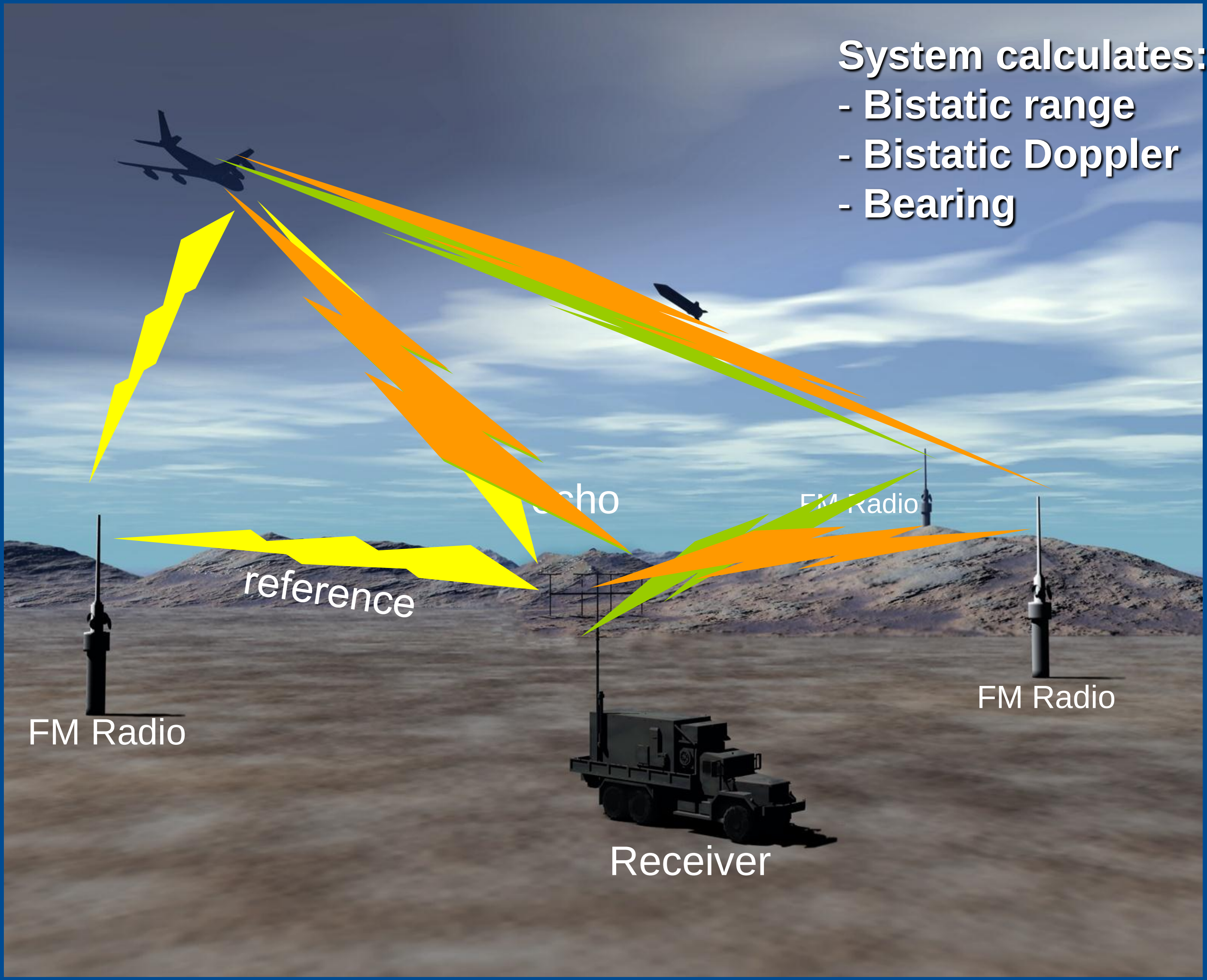
Executive Summary

- Silent Sentry sensors are valuable for critical missions
  - Air surveillance and tracking in areas of limited coverage - a "gap filler"
  - Capable of tracking low flying, non-cooperative, slow moving targets
  - Continuous total volume surveillance of air breathing and ballistic objects
  - Low acquisition and operations cost, unattended remotely managed
- Silent Sentry is ready *today* to provide operational target track data in areas of concern to support critical homeland security missions
  - Additional validation enhances performance

FM-Radio Based Bistatic Radar

Dr Paul E Howland
Sensors and Surveillance Branch
Command and Control Systems Division

System Concept

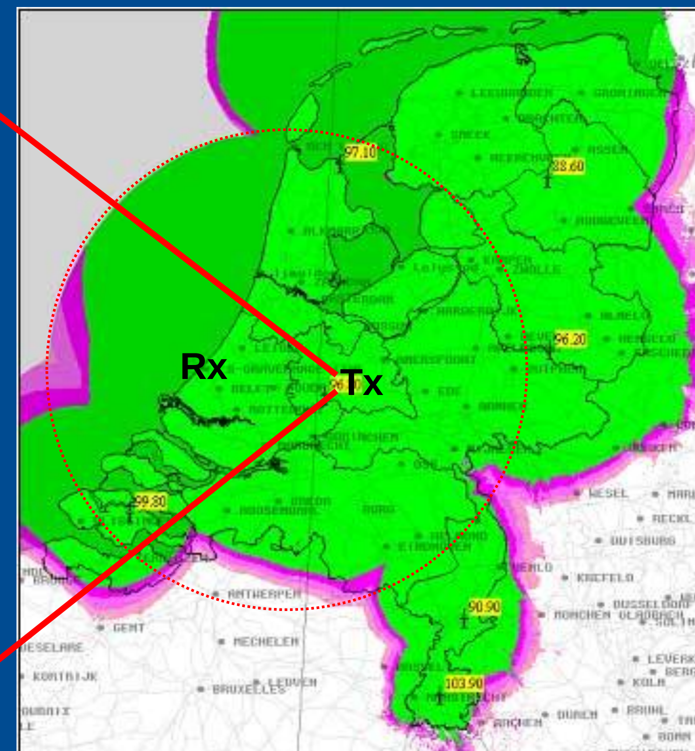


System Overview

- **One FM radio transmitter**
  - Dutch radio station at Lopik
- **One digital receiver system**
  - Located at NC3A in The Hague
- **Detect and track aircraft of opportunity**
  - Over North Sea between Netherlands and UK

FM Transmitter

- 50km from receiver
- Height 375m
- ERP 50kW
- 96.8 MHz
- V-Pol.

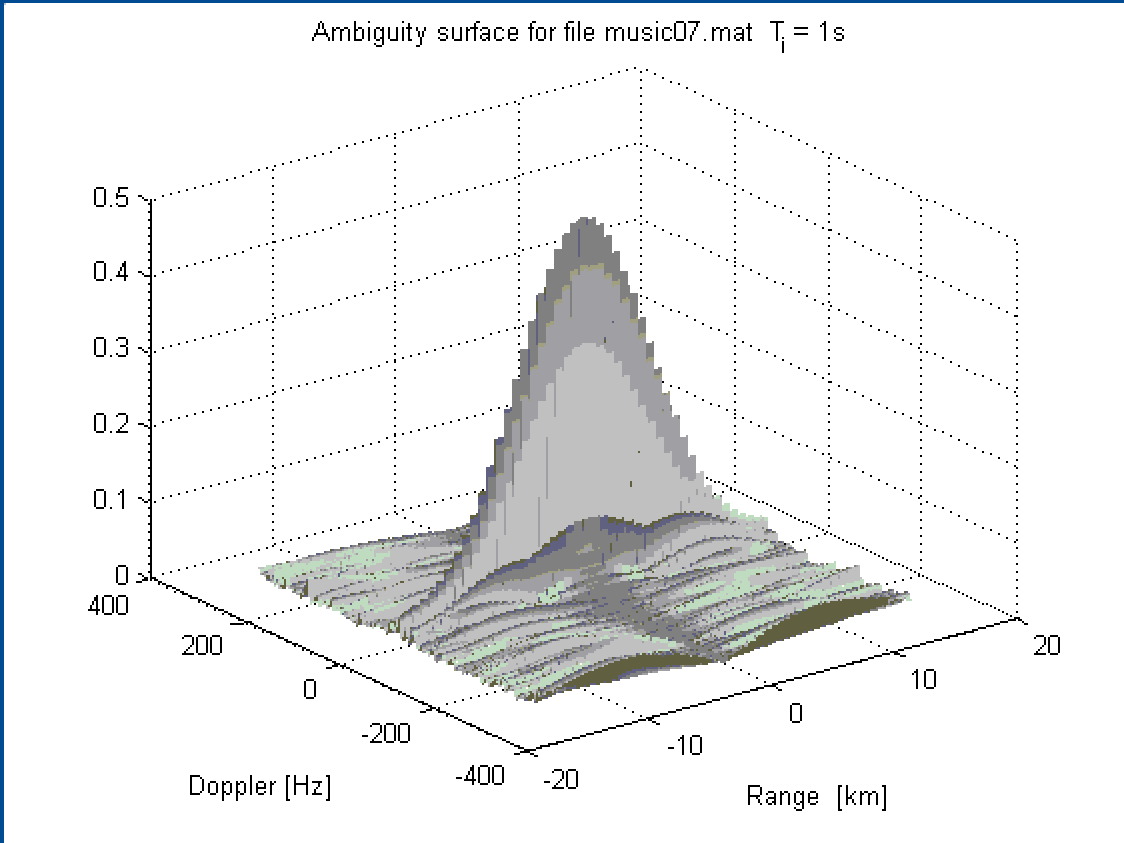


What is the Expected Performance?

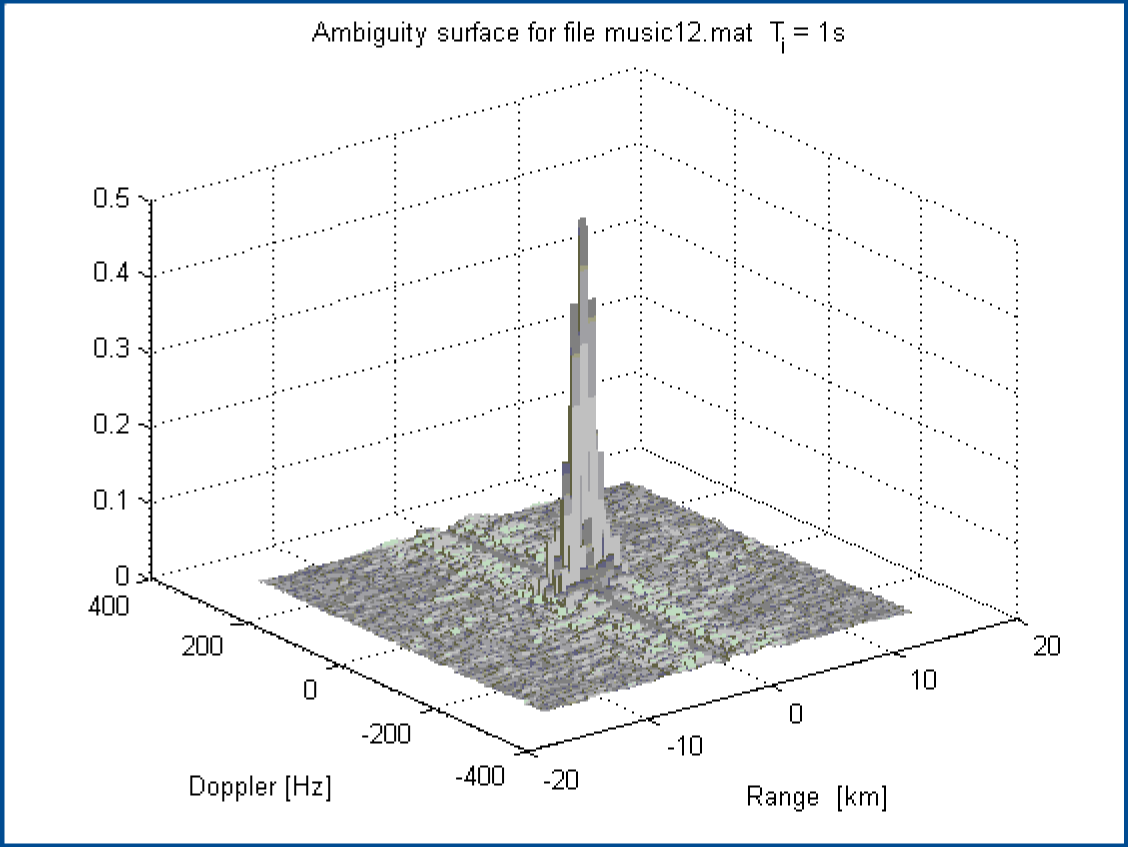
Performance is determined by:

- The coverage region determined by the basic signal-to-noise ratio
- The dynamic range requirements on the receiver due to signal-to-interference ratio
- The suitability of the FM signal as a radar signal
  - Ambiguity function

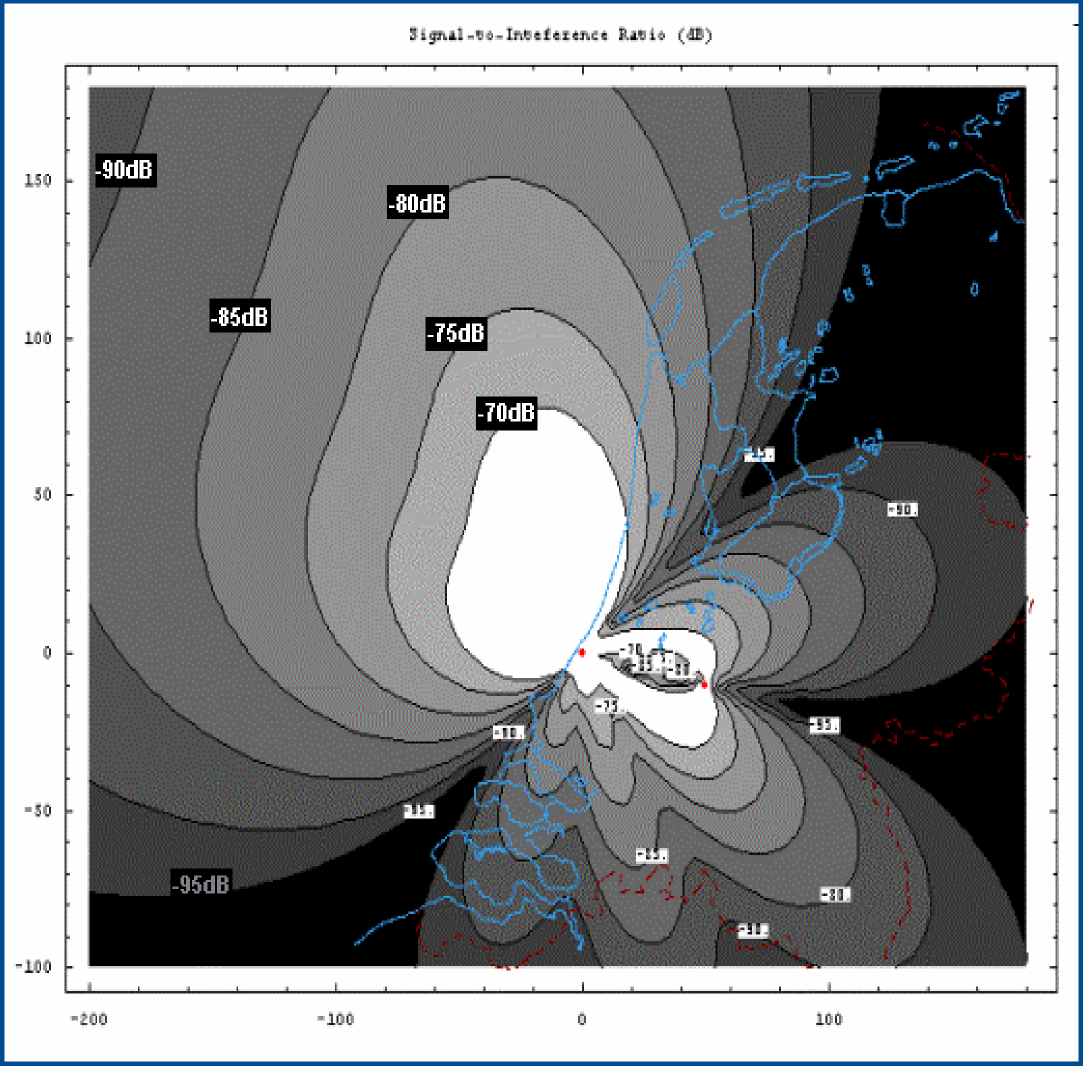
Ambiguity Surface (FM - Techno)



Ambiguity Surface (FM - Punk)



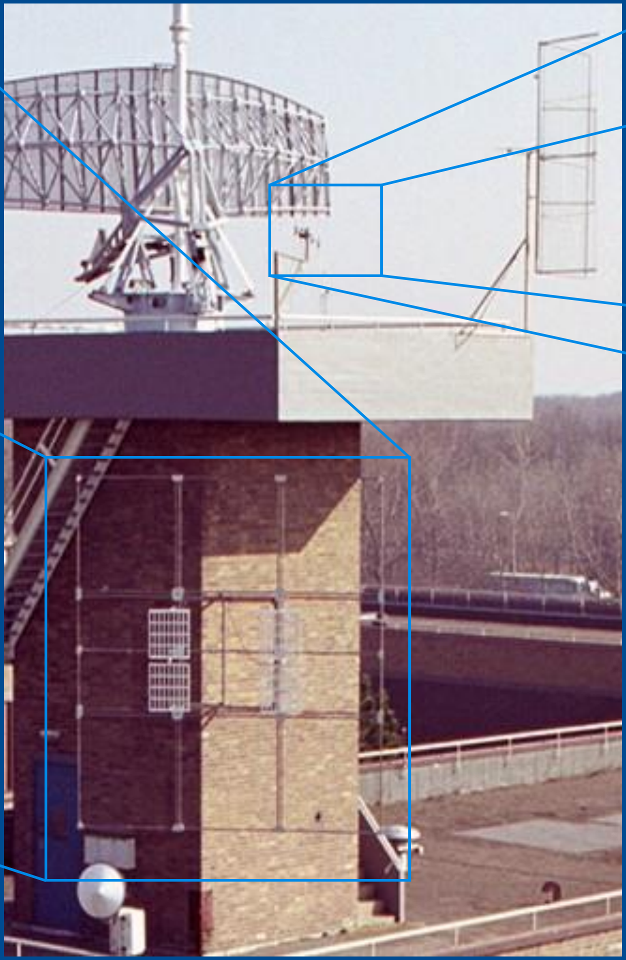
Dynamic Range Requirements



- System is dynamic range limited
- Direct signal from FM radio station masks echoes
- Figure shows ratio of echo strength to interference for $10m^2$ target
- Aggressive adaptive filtering required!

FM-Radio Bistatic Radar

Surveillance Antenna

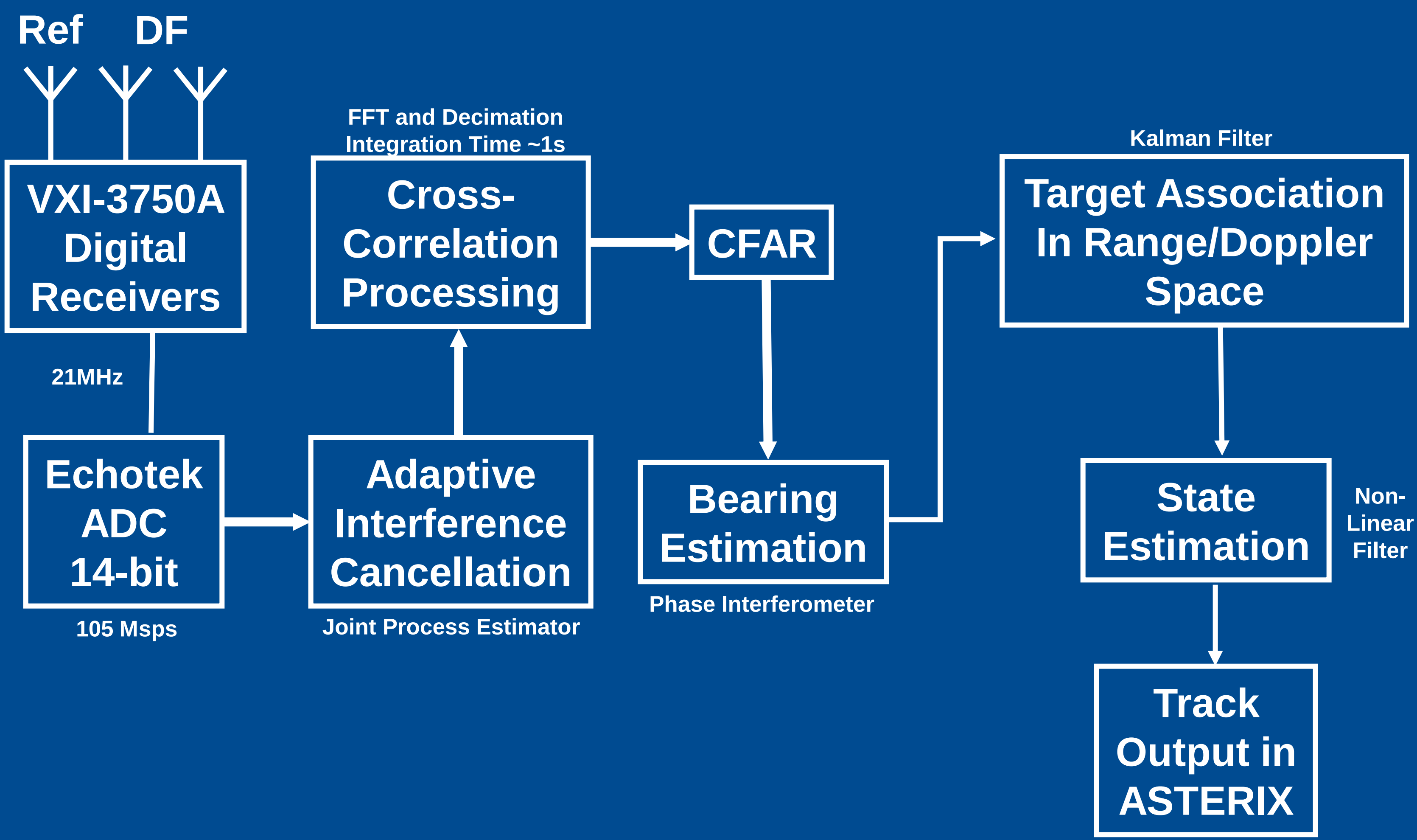


$20 Reference Antenna

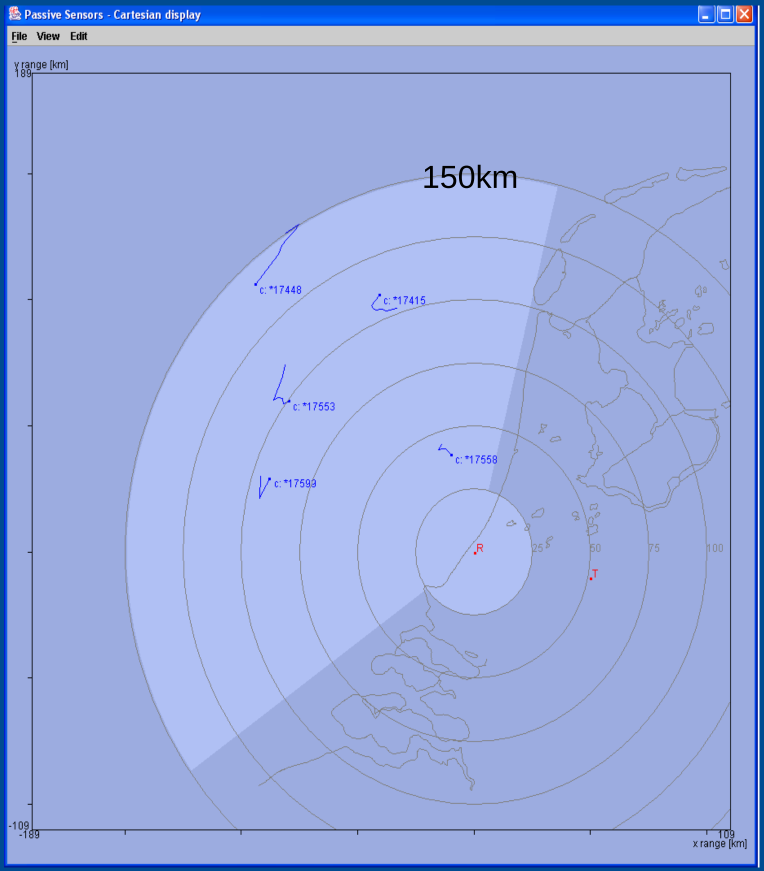
Digital V/UHF Receivers

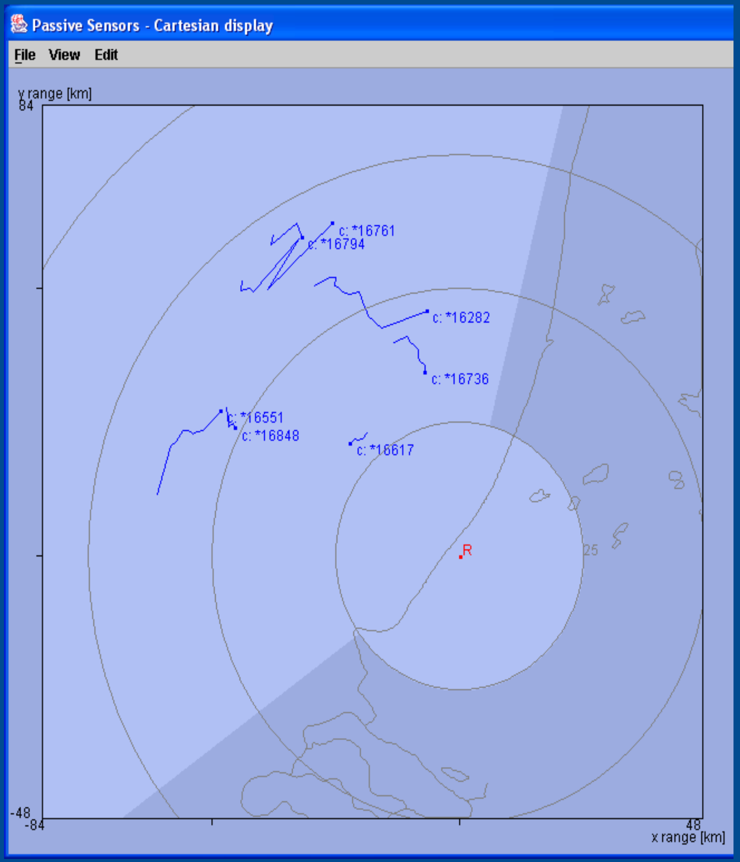
•Installed May 2002

FM-Radio Bistatic Radar
Block Diagram - 3 Channel System



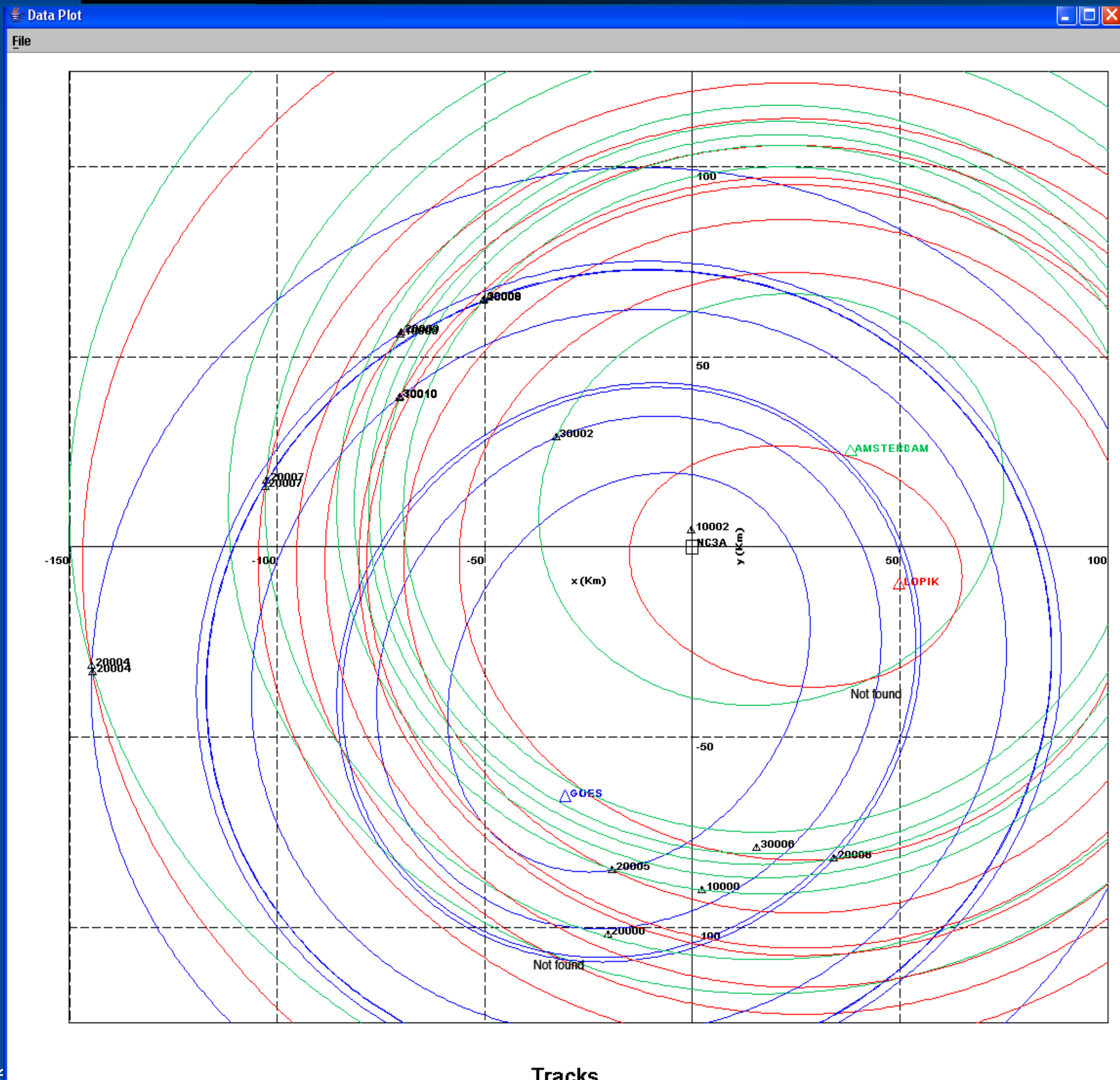
Example Tracks
(4 second update rate using 1 PC)

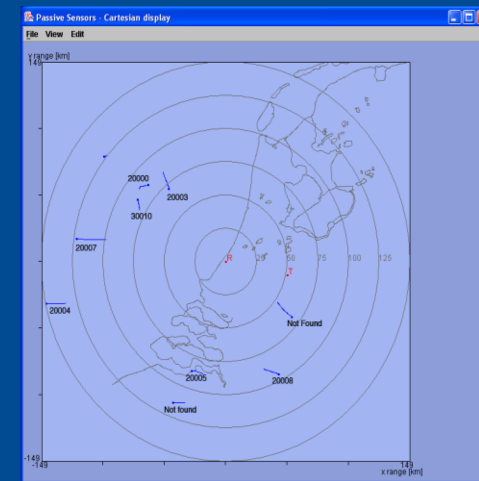




Phase interferometry used to estimate bearing – still needs calibration

Multistatic Data Association





- Which triplets of echoes from three transmitters belong to the same target?
- If this can be solved without bearing, system is much simplified
- Problem largely solved

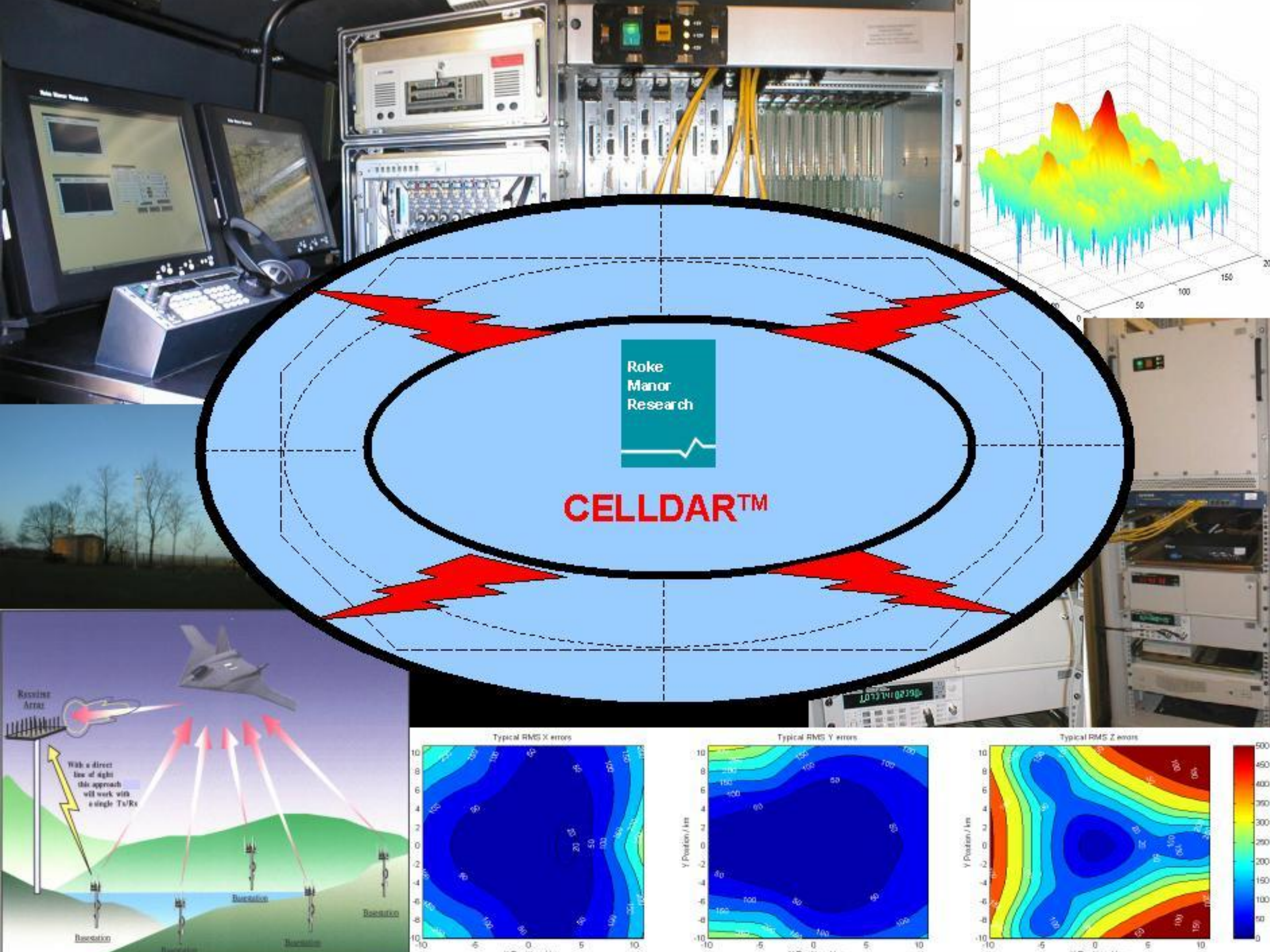
Current & Future Work

- **Eight-element receiver system**
  - Improved receivers are on order
  - Circular 8-element antenna installed
  - Data acquisition system ready
  - Initial adaptive beamforming algorithms derived

New Antenna System

- **Modifications to algorithms to handle multiple transmitters**

- **Continuing work on multistatic data association**


Roke
Manor
Research
CELLDAR™
With a direct line of sight this approach will work with a single Tx/Rx
Basestation
Basestation
Basestation
Basestation
Typical RMS X errors
Typical RMS Y errors
Typical RMS Z errors

Homeland Alerter HA-100

- **developed by THALES and ONERA in 2005**
- **FM Radio band 88 – 108 MHz**
- **8 vertical dipoles**
- **signal processing is composed of a space time algorithm to reject the direct path, estimation / correlation, regulation process and Detection / measurement. The data processing merges the detections from all 8 channels to tracks in Cartesian coordinates. The update rate is 1.5 s**

THALES

Selex AULOS

- **developed by THALES and ON in 2005**

Passive Radar at UW

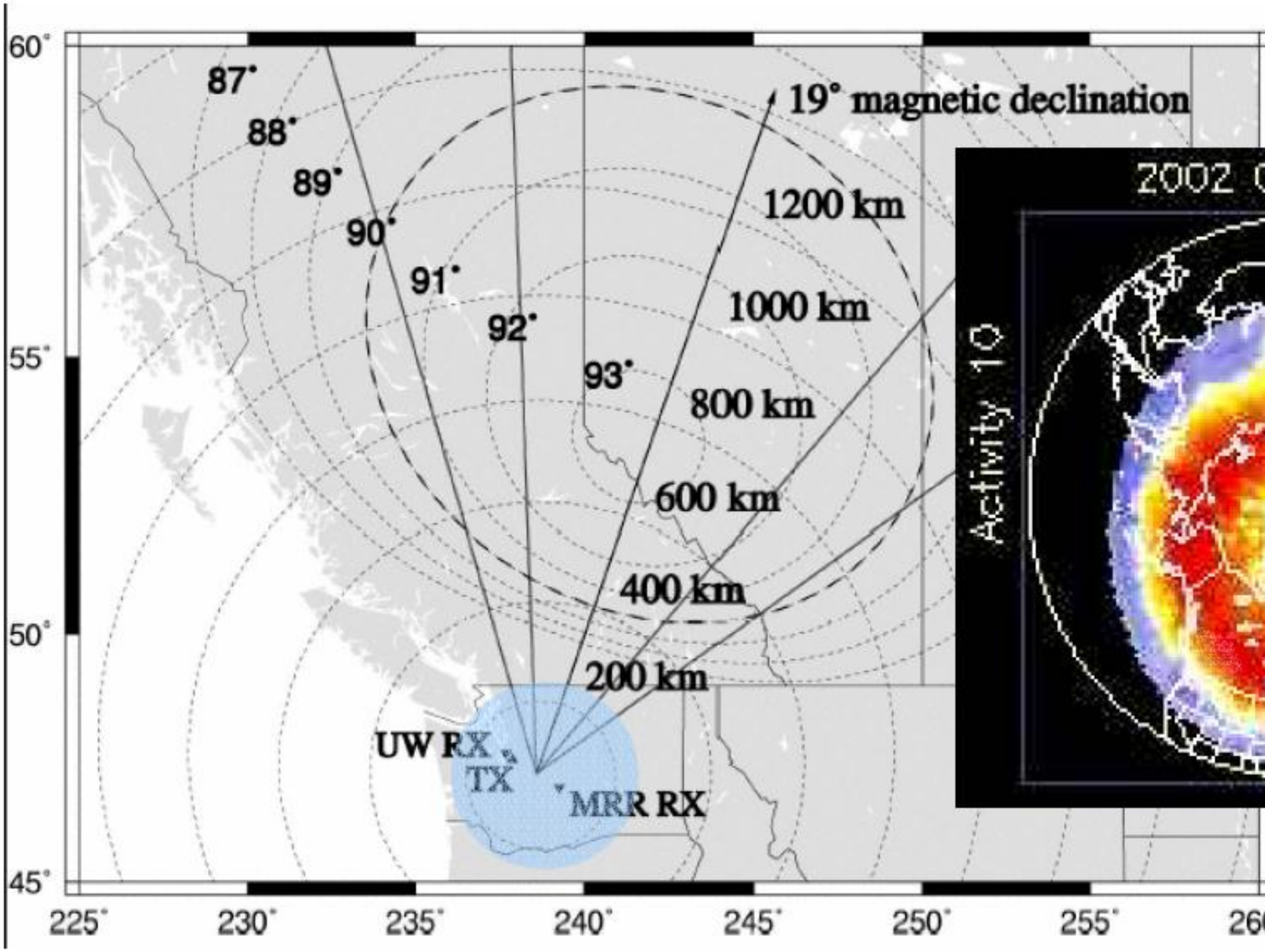
Tool for study of plasma turbulence at the base of the Northern Lights

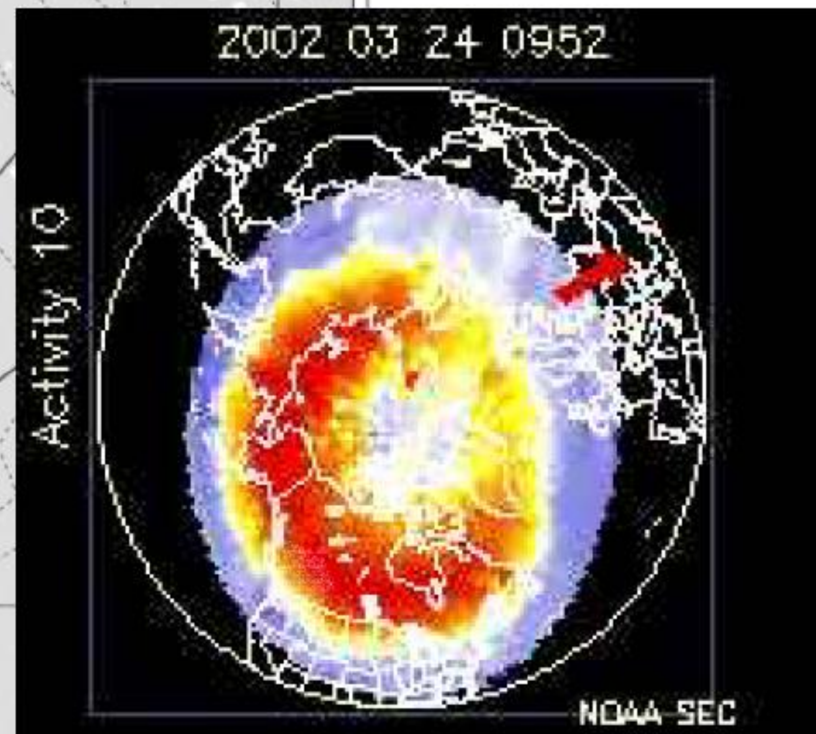
Why?

- The physics is interesting
- The radar target is challenging (deep, fluctuating target)
- Ionospheric turbulence degrades spacecraft communications and radio navigation systems

º Photo by Jan Curtis

Radar Field of View





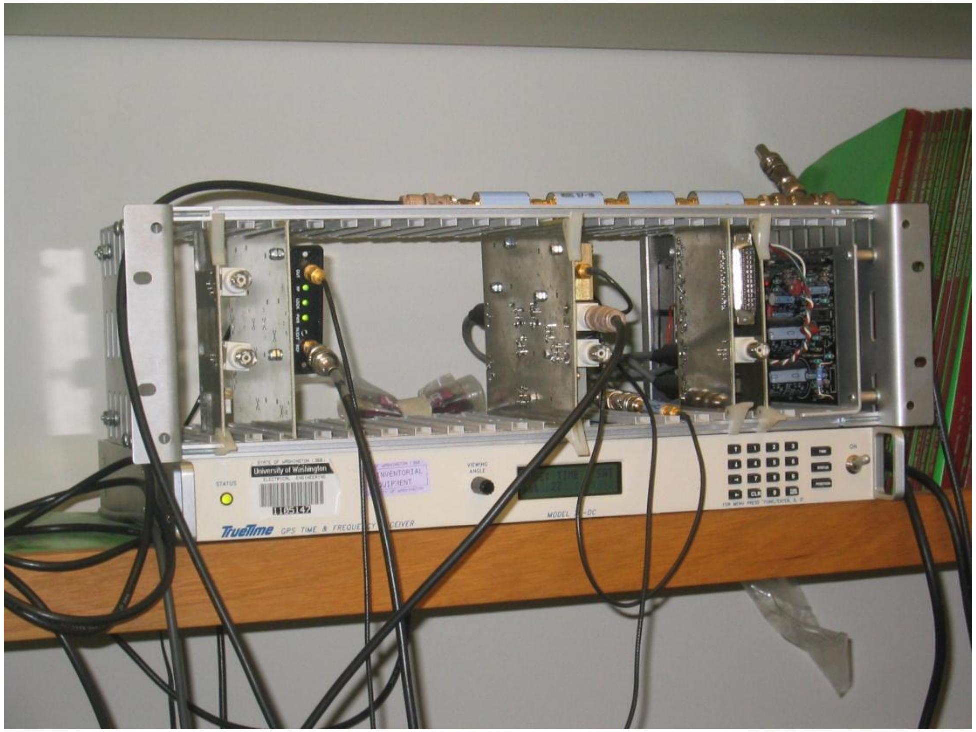
Why Passive Radar?

- Conventional radars work fine, but
  - Expensive transmitters: $200k for 50 kW
  - Safety issues (academic environment)
  - Operating cost
  - Licensing
- Need meter scale: 100 MHz is perfect
- Lots of 100 MHz power for free
- Performance is the goal, not "passive radar"

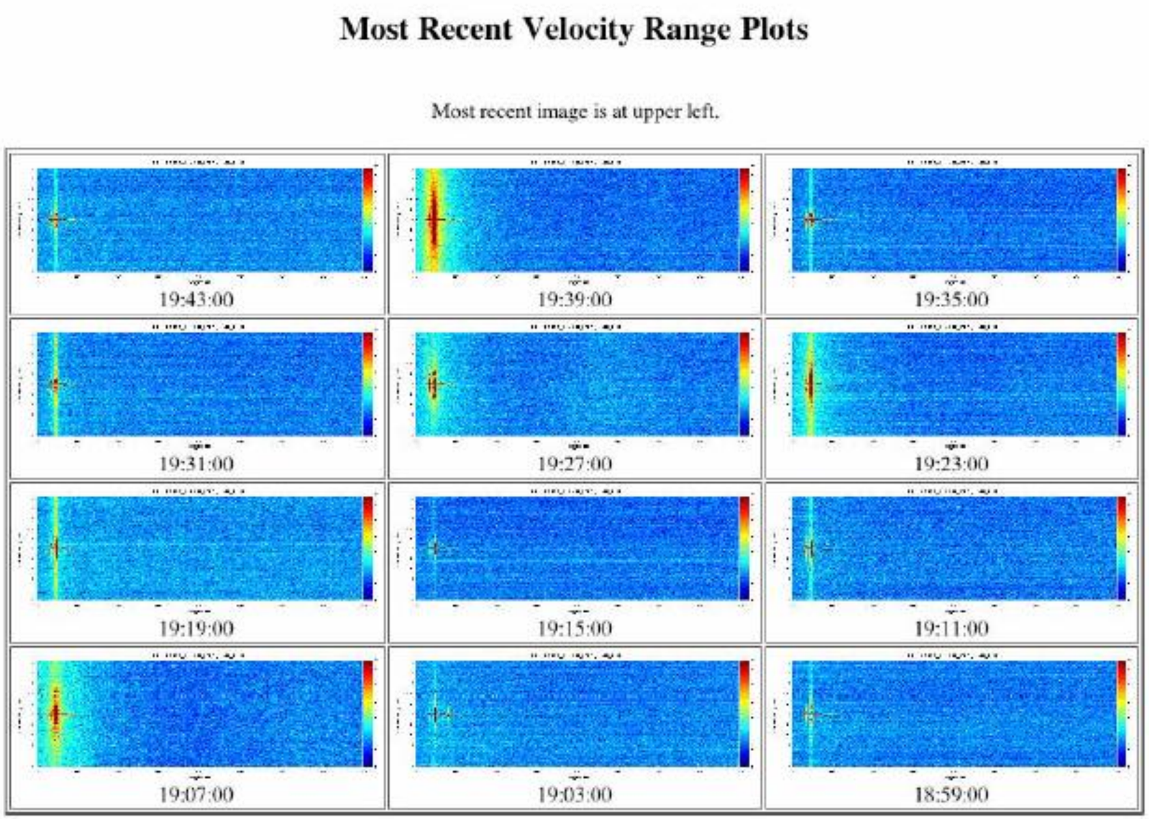
Split Receiver Topology

- Direct illumination much stronger than scattered signal: 100 dB or more
- Engineering skill to build large dynamic range receivers probably exceeds available human capital resources (me and my students).
- Split Receiver topology solves this problem
  - Reference near TX
  - Scatter RX well separated: 150 km, mountain range
- However, generates synchronization and transport issues: solved with GPS and internet, off the shelf!

Manastash Ridge Radar receiver



MRR Real-Time Data Products



Range-Doppler Output

New frames every 4 minutes

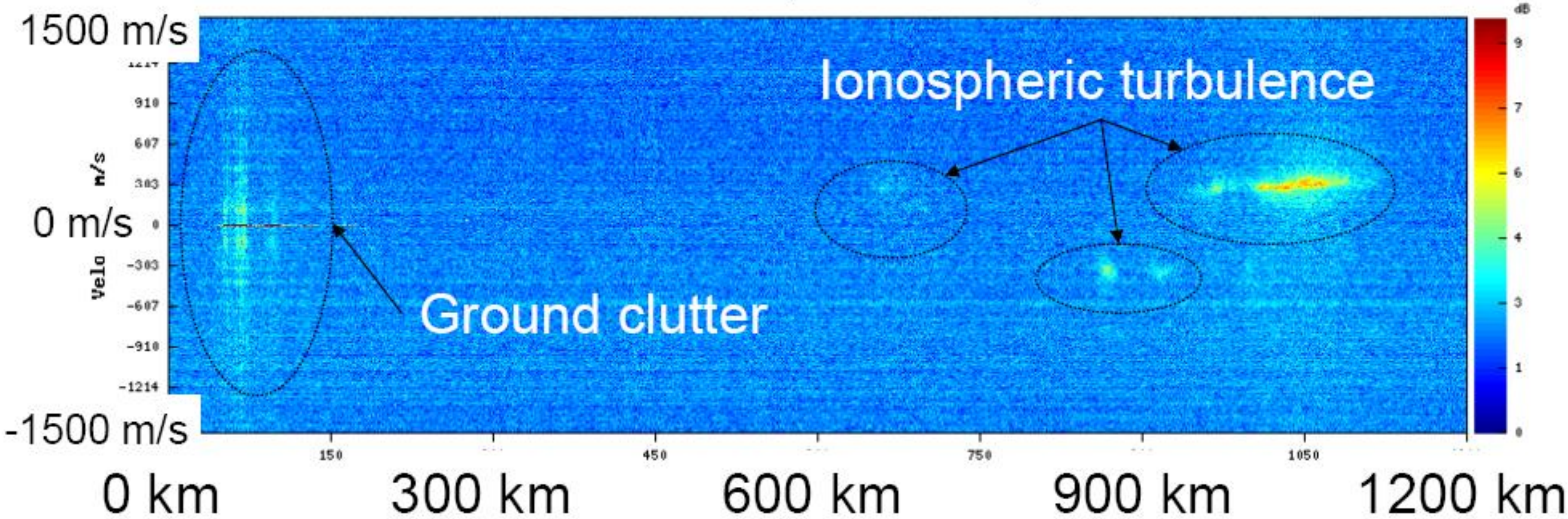
WWW page updated every half hour

0-1200 km
+/- 1500 m/s

See http://rrsl.ee.washington.edu/Data

Finer Range-Doppler Detail

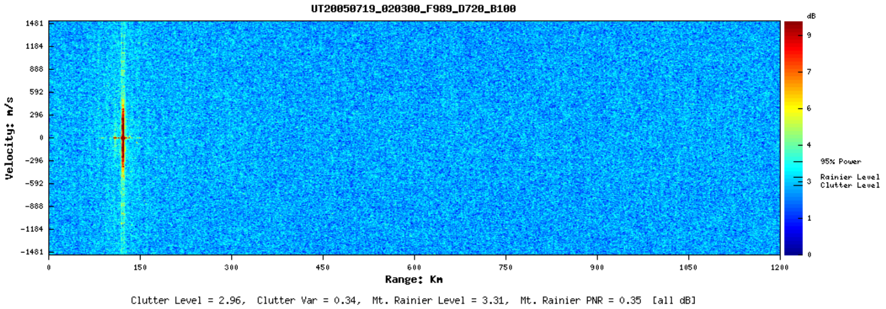
17 October 2003, 0843 UT, 96.5 MHz



This is the standard online data product,
Produced automatically 24/7
10 seconds of data sampled every 4 minutes
Visible on our WWW page within 30 minutes

Manastash Ridge Radar

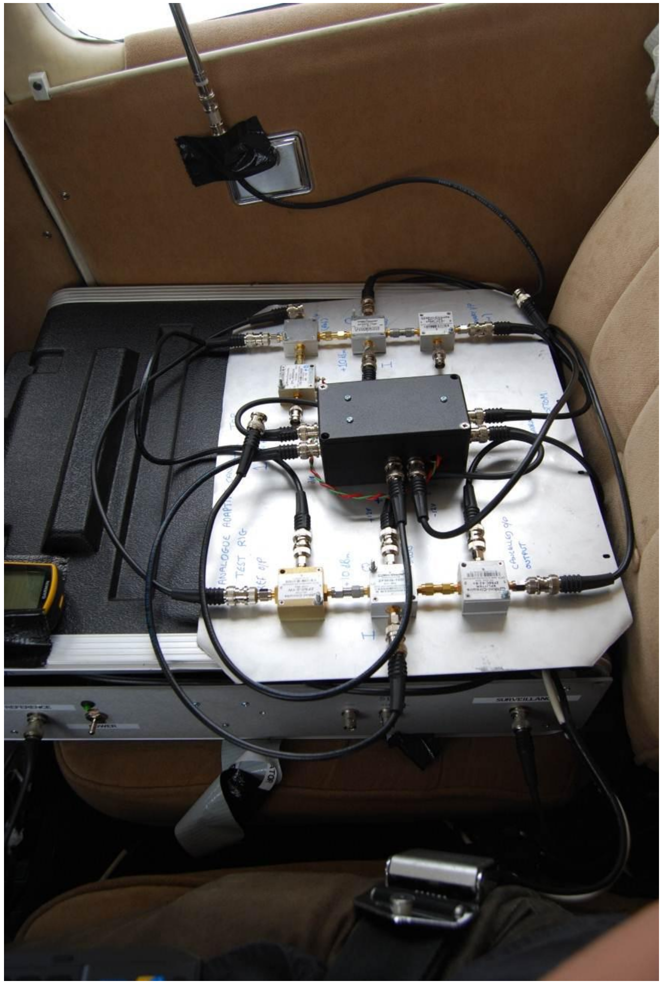
If you look closely at the attached range-Doppler, there are a couple aircraft echoes visible; later range-Dopplers show many more, and more obviously (ignore remarks about Mt Rainier; that annotation is left over from the original radar link). The most significant red mark is direct path leakage. Note that there are no significant mountains obstructing the MRO--- Spokane path; just distance.



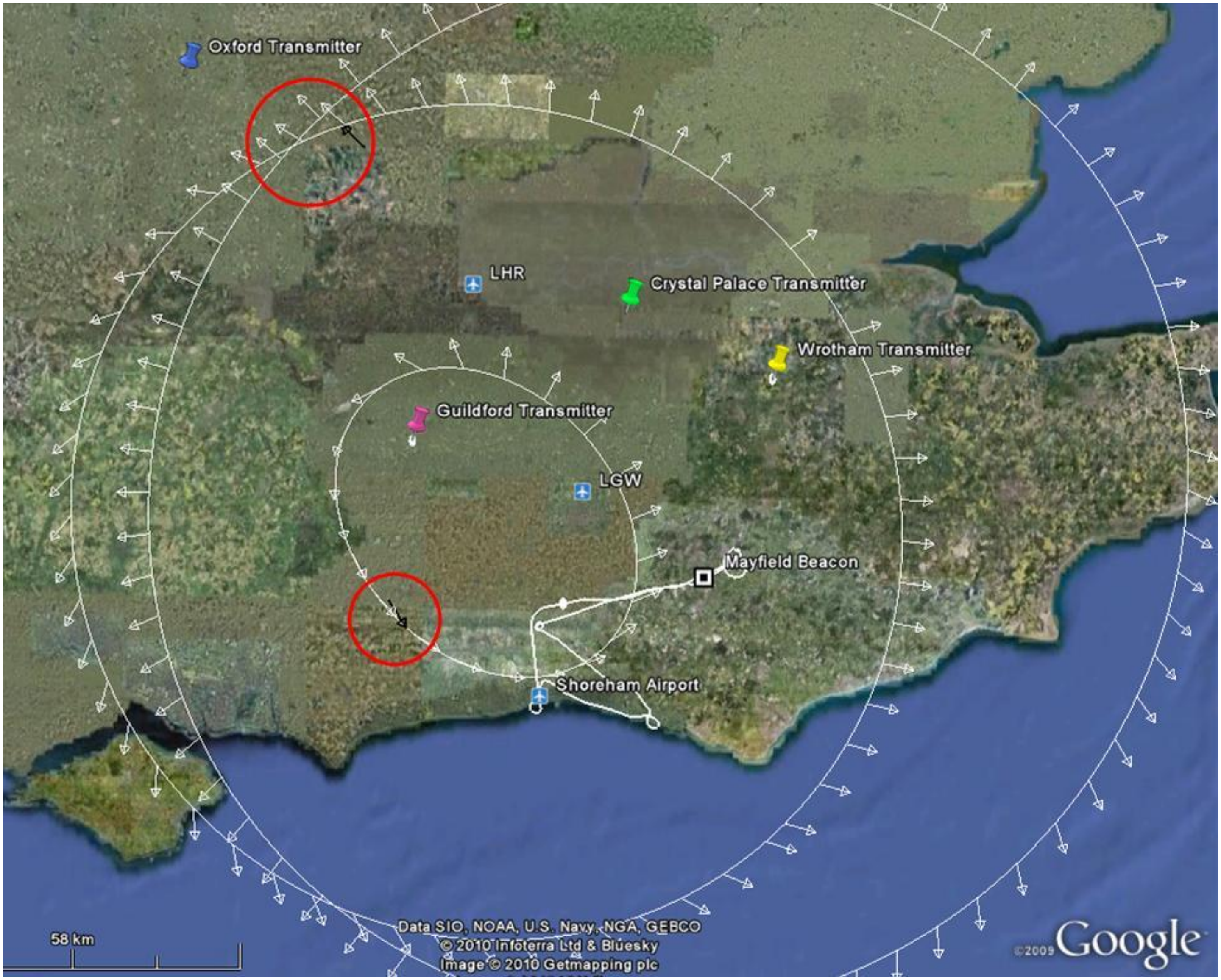
My students Zac and Melissa set up the third (NATO-funded) receiver in the Physics Department at Eastern Washington University (near Spokane, WA) about a week ago; and last weekend we reinstalled the Ellensburg receiver (down for some work). Except for one blown power supply, it worked more or less immediately.

The receiver (named kennewick) is much better integrated than the other two; all the "bits & pieces" are within the computer cabinet (except for the antennas). The GPS antenna and the dipole are visible in the window; note that both are completely inside the building.

PBR with an aircraft-borne receiver



PBR with an aircraft-borne receiver

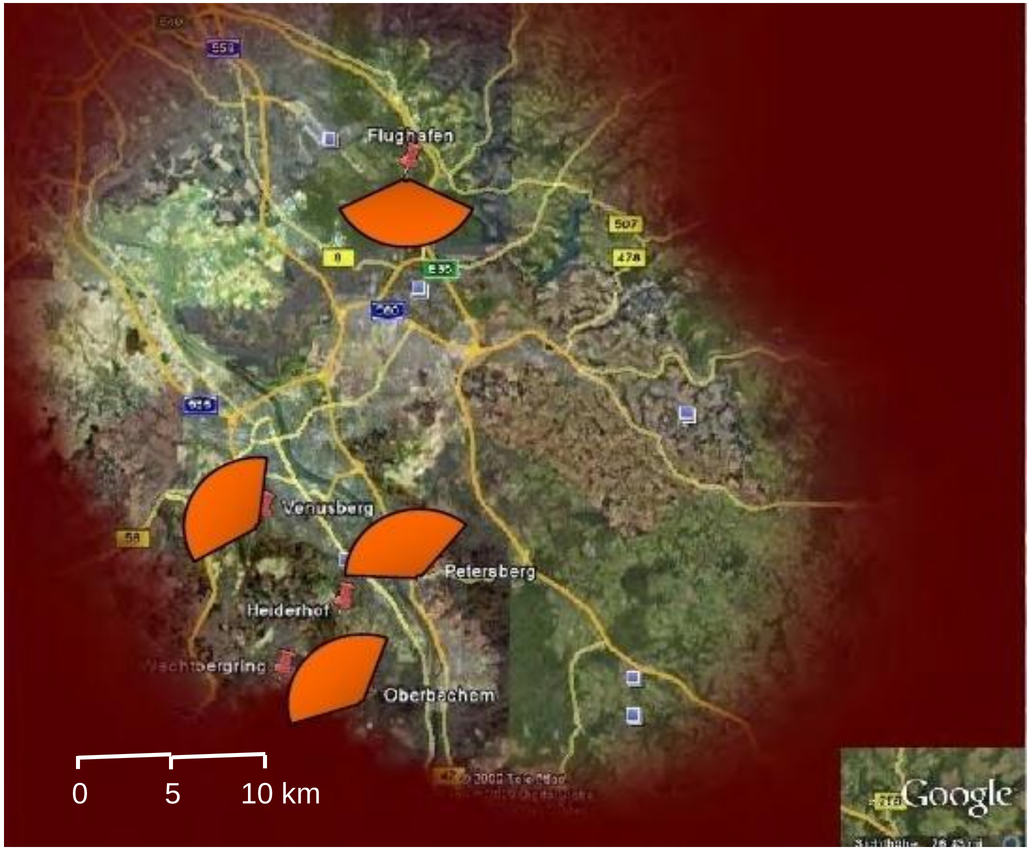


GSM-based PBR (Singapore)

- Tan et al. reported experimental results with a 25 W GSM basestation transmitter in Singapore.
- The 81.3 kHz signal bandwidth provides only coarse range resolution (coarser than the expected maximum detection range), which meant that they were constrained to using Doppler-only processing.
- They reported detection and tracking of large vehicle targets at ranges up to 1 km, and of human targets up to about 100 m.

D.K.P. Tan, H. Sun, Y. Lu, M. Lesturgie and H.L. Chan, 'Passive radar using Global System for Mobile communication signal: theory, implementation, and measurements', Special Issue of *IEE Proc. Radar, Sonar and Navigation* on Passive Radar Systems, Vol.152, No.3, pp116–123, June 2005.

GSM-based PBR (Fraunhofer FHR, Germany)



GPS-based PBR

- Early experiments in Germany used forward scatter and long integration times (~ 1s) to detect military and civil aircraft, an anti-tank missile, and the MIR Space Station

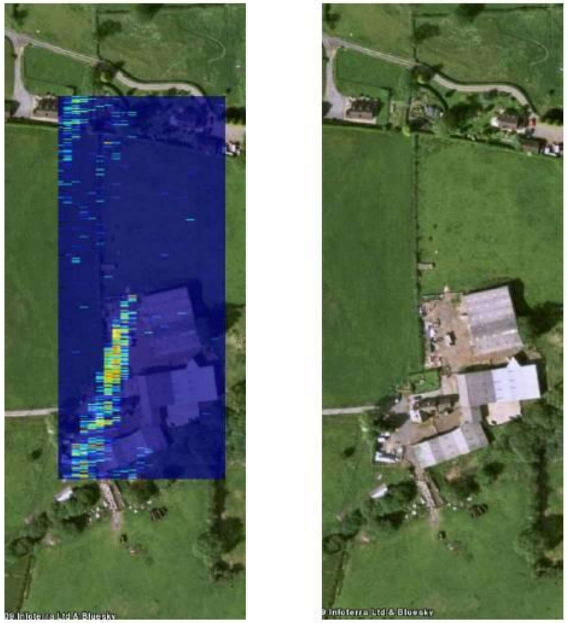
- More recent work by Cherniakov at the University of Birmingham has used GALILEO transmissions for synthetic aperture imaging

V. Koch and R. Westphal, 'A new approach to a multistatic passive radar sensor for air defense', *Proc. IEEE International Radar Conference RADAR 1995*, Washington DC, IEEE Conf. Publ No.95CH3571-0, pp22-28, 8-11 May 1995.

V. Koch and R. Westphal, 'New approach to a multistatic passive radar sensor for air/space defense', *IEEE AES Magazine*, Vol.10, No.11, pp24-32, November 1995.

GNSS-based PBR SAR

frequency channel	10 (1607.625 MHz)
satellite azimuth θ_A	178.4914º
satellite elevation θ_E	11.3558º
bistatic angle β	~ 11º
satellite altitude	~ 23 000 km
aperture length	26.78 m
integration time	45 s
receiver velocity	~ 0.6 m/s
receive antenna gain	16 dBi, effective area 0.11 m^2.



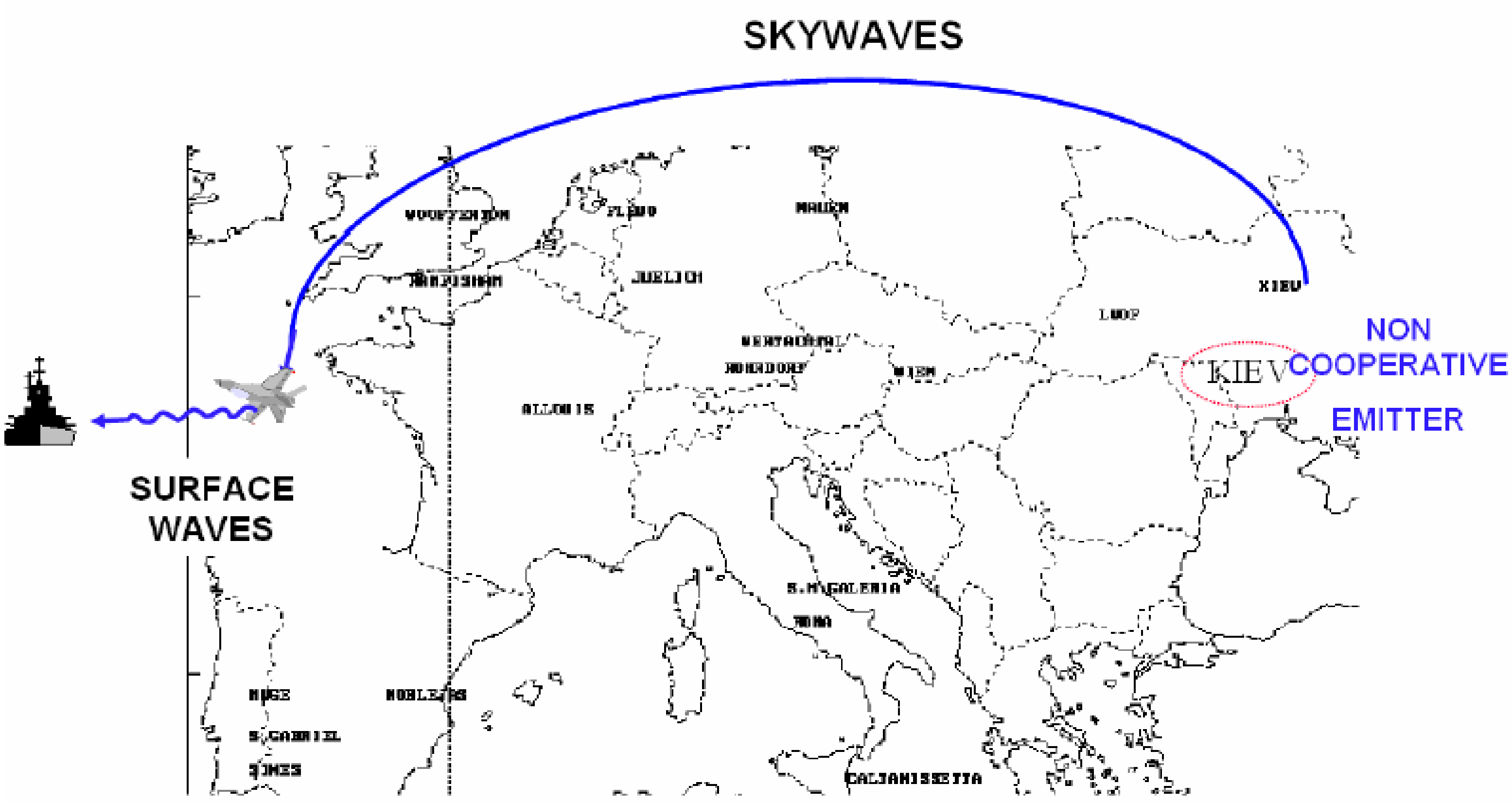
M. Cherniakov, R. Saini, R. Zuo and M. Antoniou, ‘Space-surface bistatic synthetic aperture radar with global navigation satellite system transmitter of opportunity – experimental results’, Special Issue of *IET Radar, Sonar and Navigation* on EMRS DTC, Vol.1, No.6, pp447-458, December 2007.

M. Antoniou, R. Zuo and M. Cherniakov, 'Passive space-surface bistatic SAR imaging’, *7th EMRS DTC Technical Conference*, Edinburgh, 13/14 Jul 2010.

Passive radar – re-use of HF emitters

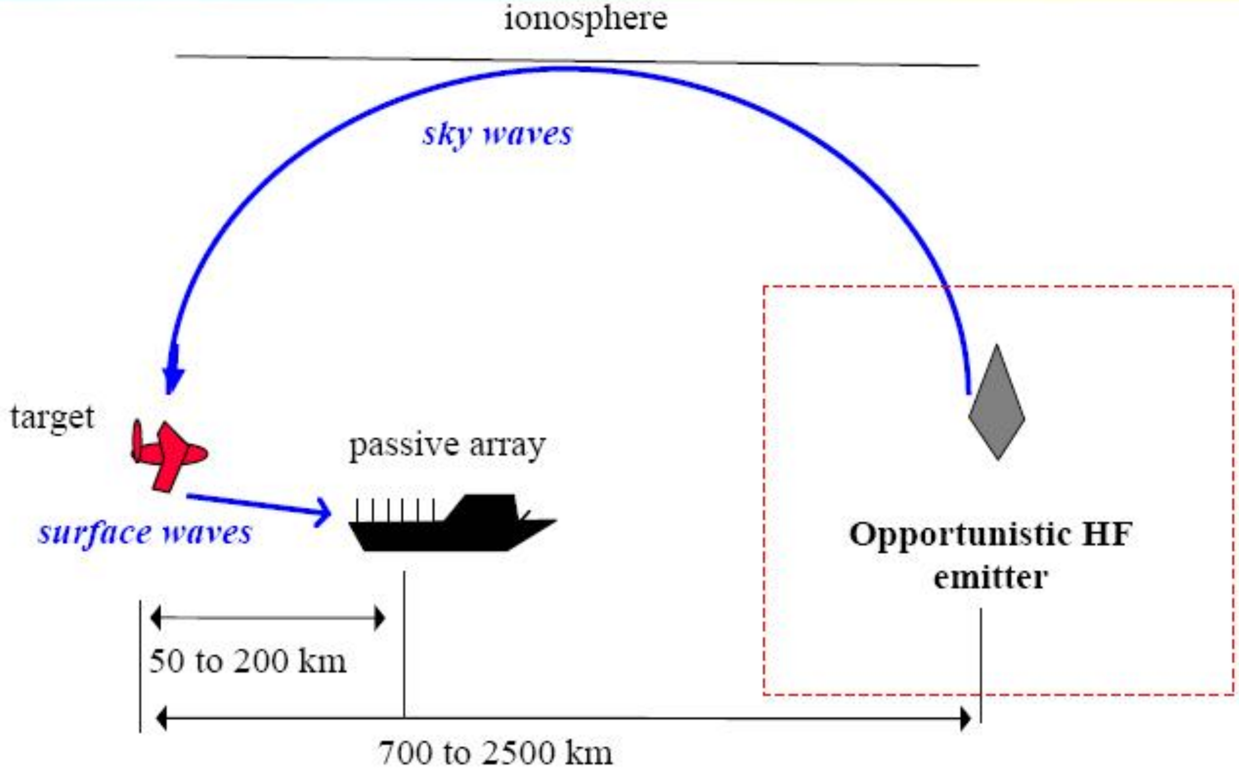
- INTEREST
- EXAMPLES
- HF-OTH
- HF-SWR
- FOPEN
- BISTATIC
- **PASSIVE**

over the horizon passive detection



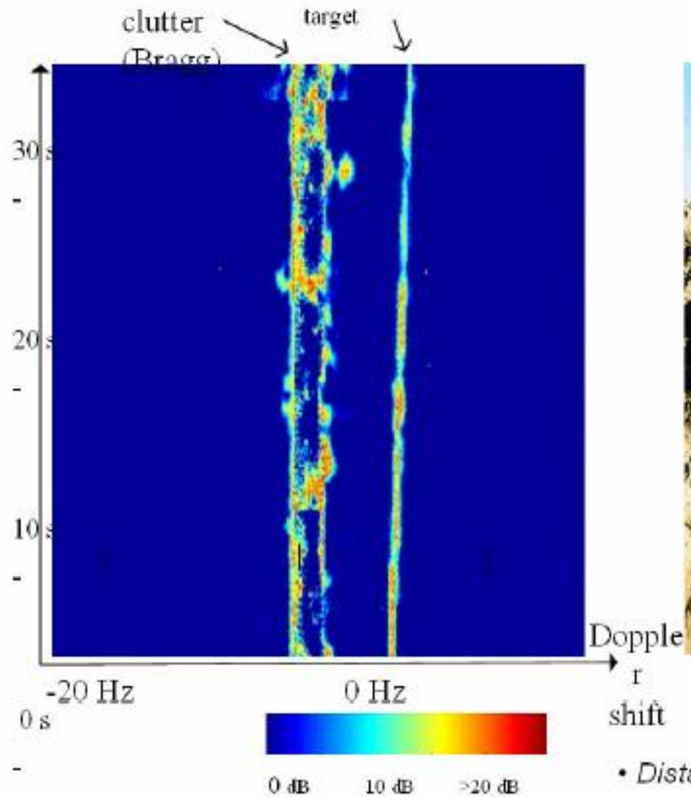
From M. Lesturgie, M. Flécheux - « *Nostramarine: un concept de détection multistatique adapté à la surveillance des cibles basse altitude* » - AGARD - CP 595 - 1997

Passive radar – re-use of HF emitters



- Ship borne passive array
- Full digital beam forming & Doppler processing
- Over the horizon (OTH) capabilities

Example - Use of Kiev emitter



- *Distance = 75 km, alt. 300 ft (fighter class)*
- ***RADAR Line of Sight : 40 km***

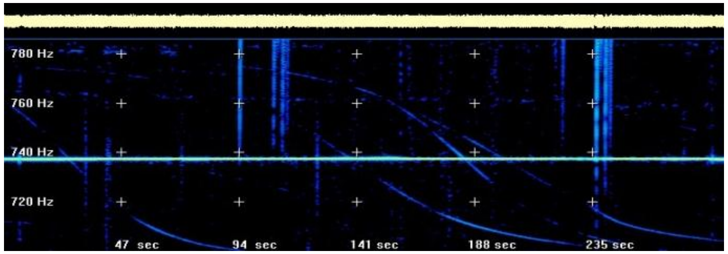
Some HF amateur radio experiments

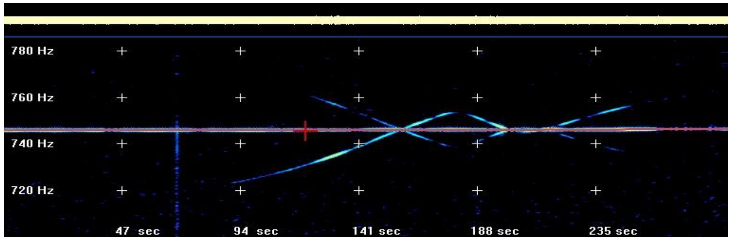
- **time series plots of spectra associated with carrier of HF signal from transmitter at ~100 km range**

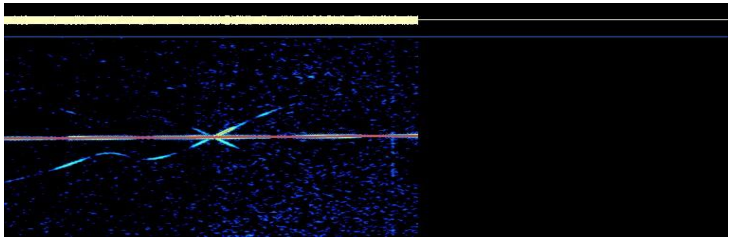
- **shows Doppler shifted traces due to aircraft**

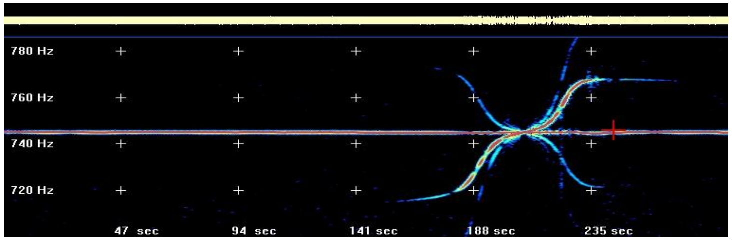
- **Do try this at home !**

- **can download spectrogram software**









http://www.qsl.net/g3cwi/doppler.htm