Altair Technology Conference

Israel 2019

Dynamical RCS - Helicopters in pulsed Doppler radars image.

Officer Tal Oz, 30.10.19

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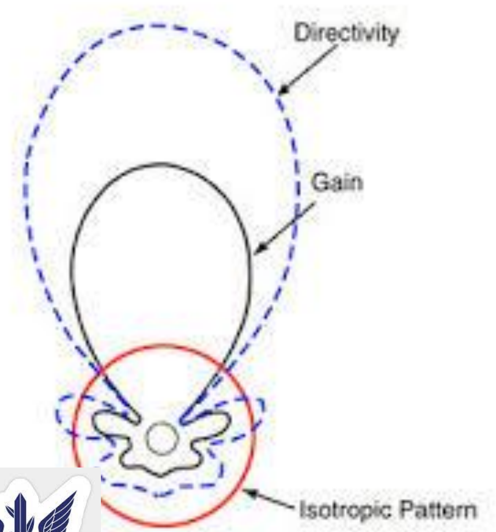
How does a pulsed Doppler radar work

What is a radar?

It all starts with an antenna.

Direction detection

- Angle detection is based on the antenna directivity.

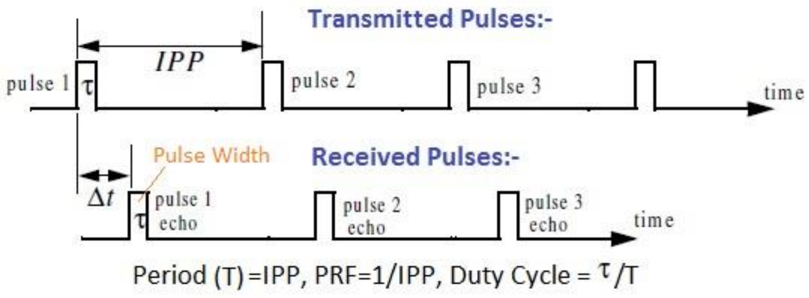


Range detection

- A Radar sends a pulse, after some time t, the radar receives a pulse.

$$R = \frac{ct}{2}\ [example: R = 75km, t = 0.5ms]$$

- After some time PRI, the radar sends another pulse.



- I will not talk about PRI, lets just assume $PRI \sim 0.5ms$.

Radar signal power

1. A radar transmit radiation in a specific direction.
2. Free space propagation (radial decay).
3. The target scatters some of the radiation backwards.
4. Free space propagation (radial decay).
5. The radar receives the radiation.

$$P_r = \overbrace{P_t G}^{1} \overbrace{\frac{1}{4\pi R^2}}^{2} \overbrace{\boldsymbol{\sigma}}^{3} \overbrace{\frac{1}{4\pi R^2}}^{4} \overbrace{\frac{G\lambda^2}{4\pi}}^{5}$$

Radar signal phase

$$\phi = \phi_{tx} + 2\pi \cdot \frac{R}{\lambda} + \phi_{\sigma} + 2\pi \cdot \frac{R}{\lambda} + \phi_{Rx}$$

1. The Tx and Rx impose some unknown constant phase.
2. The free space propagation adds R/λ phase.
3. The backscattering (RCS) itself add some phase.

Moving target signal

- Moving target radial distance:

$$R = R_0 + V_r t \rightarrow \phi_r = 2\pi \frac{R_0}{\lambda} + 2\pi \frac{V_r PRI}{\lambda}$$

- Amplitude difference between consecutive pulse:

$$\frac{1}{R_0^4} - \frac{1}{(R_0 + V_r PRI)^4} \approx 4 \frac{V_r PRI}{R_0} \ll 1$$

- Phase difference between consecutive pulse:

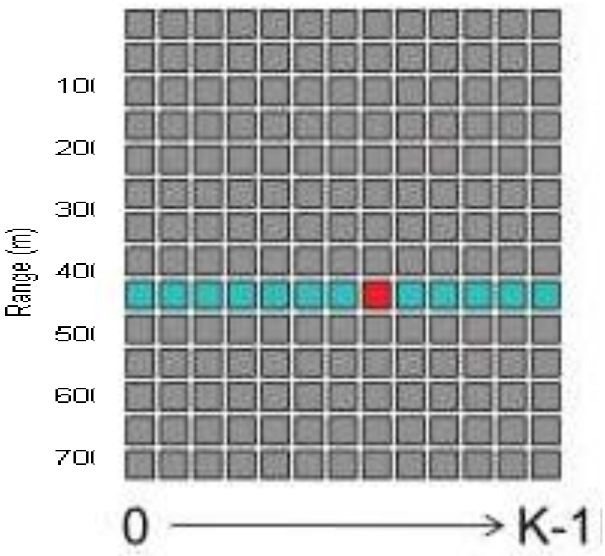
$$\Delta\phi_n \equiv \phi_n - \phi_1 = (n-1) \cdot 2\pi \cdot \frac{\mathbf{2} V_r PRI}{\lambda}$$

Pulsed Doppler radar

- A radar sends N pulses at a constant PRI.
- Two time axes are defined:
  fast time – the time for the pulse return.
  Slow time – pulse number * PRI.
- Lets examine the FFT of the slow time:

$$FFT\left(e^{2\cdot\frac{2\pi i}{\lambda}\cdot v_r t_{slow}}\right)\sim\delta(f-f')$$

- 0 Doppler targets – trees, mountains, birds.



Regular target Doppler variation

- Consider a fighter jet, over the course of 32 pulses of PRI $625\mu s$

$$t = 20ms$$

- Maneuver acceleration, usually up to $10g \rightarrow \delta v \sim 2m/s$
- Change in RCS: $\sigma \sim \frac{\partial \sigma}{\partial \theta} \delta \theta$

  Change of flight angle $\delta \theta \sim \frac{\delta v}{v} \sim 0.01[rad]$
- Overall, very small variations around $\exp\left(2i \cdot \frac{2\pi}{\lambda} v_r t\right)$ this leads to weak smear of the signal.

Helicopter Doppler variation

- Consider a helicopter, over the course of 32 pulses of PRI $625\mu s$

$$t = 20ms$$

- Velocity change – negligible.
- 4 blade rotor, with RPM of 380:

$$N_{rounds} = t \cdot rpm \cdot 4 \approx 0.5$$

- Blade edge velocity:

$$2\pi * rpm * L \sim 360m/s$$

- Blade edge translation:

$$\delta r = v \cdot t = 7.2m$$

- What would the range-Doppler signal of a helicopter look like?

Dynamical helicopter RCS

- For incident field E_h

$$E_{hh} \propto \sqrt{\sigma_{hh}} e^{i\phi_\sigma} E_h e^{2i\cdot\frac{2\pi}{\lambda}\cdot v_r t}$$

  (lets assume $v_r = 0$)
  definition $\sqrt{\sigma}' \equiv \sqrt{\sigma_{hh}} e^{i\phi_\sigma}$

- Range Doppler signal:

$$\underset{time}{FFT_{slow}}(E_{hh}) \rightarrow \underset{time}{FFT_{slow}}\left(\sqrt{\sigma}'\right)$$

- To get $\sqrt{\sigma}'(t)$ we can use Feko by calculating $\sqrt{\sigma}'(\theta)$ and transfer $\theta \rightarrow t$ using the helicopter's RPM.

How is RCS calculated

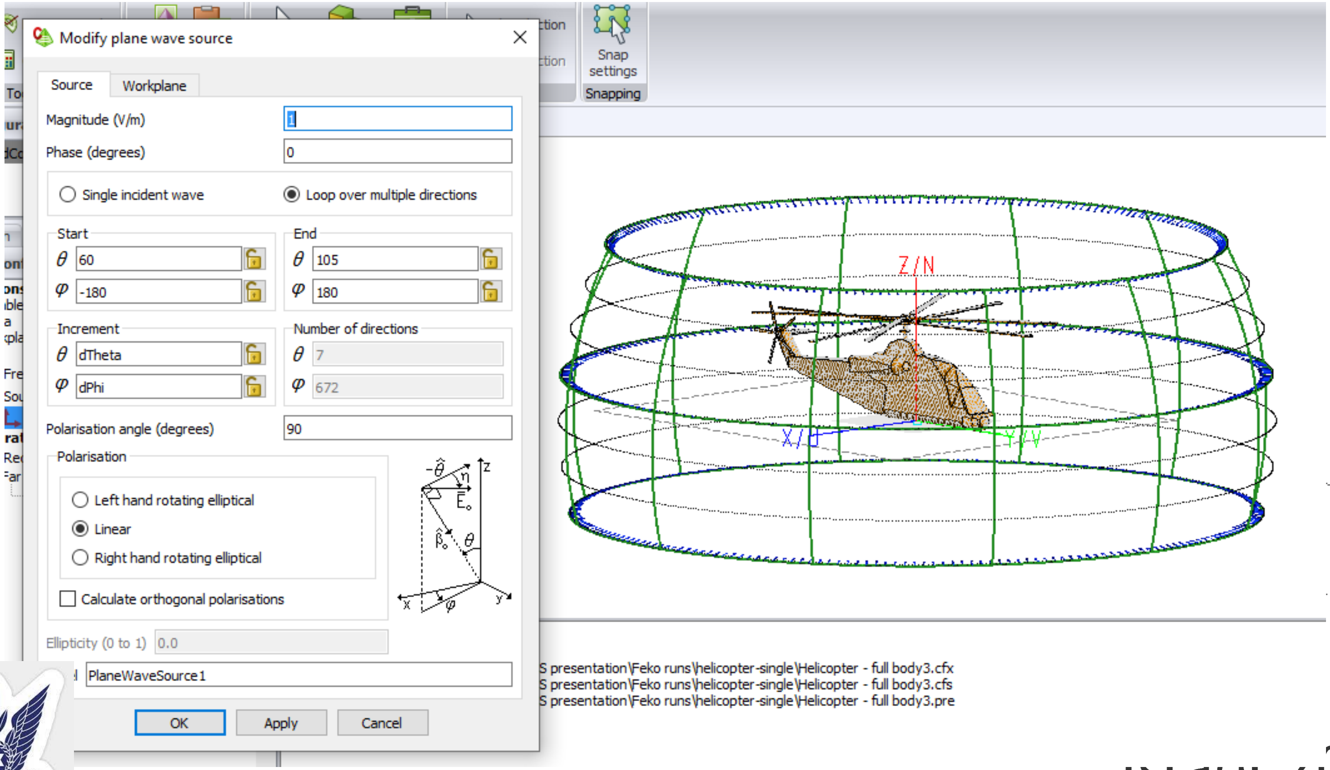
Method of Momenths

- Incident plane wave
- Metallic body (helicopter)
- Wavelength dependent mesh of the body
- Maxwell equations

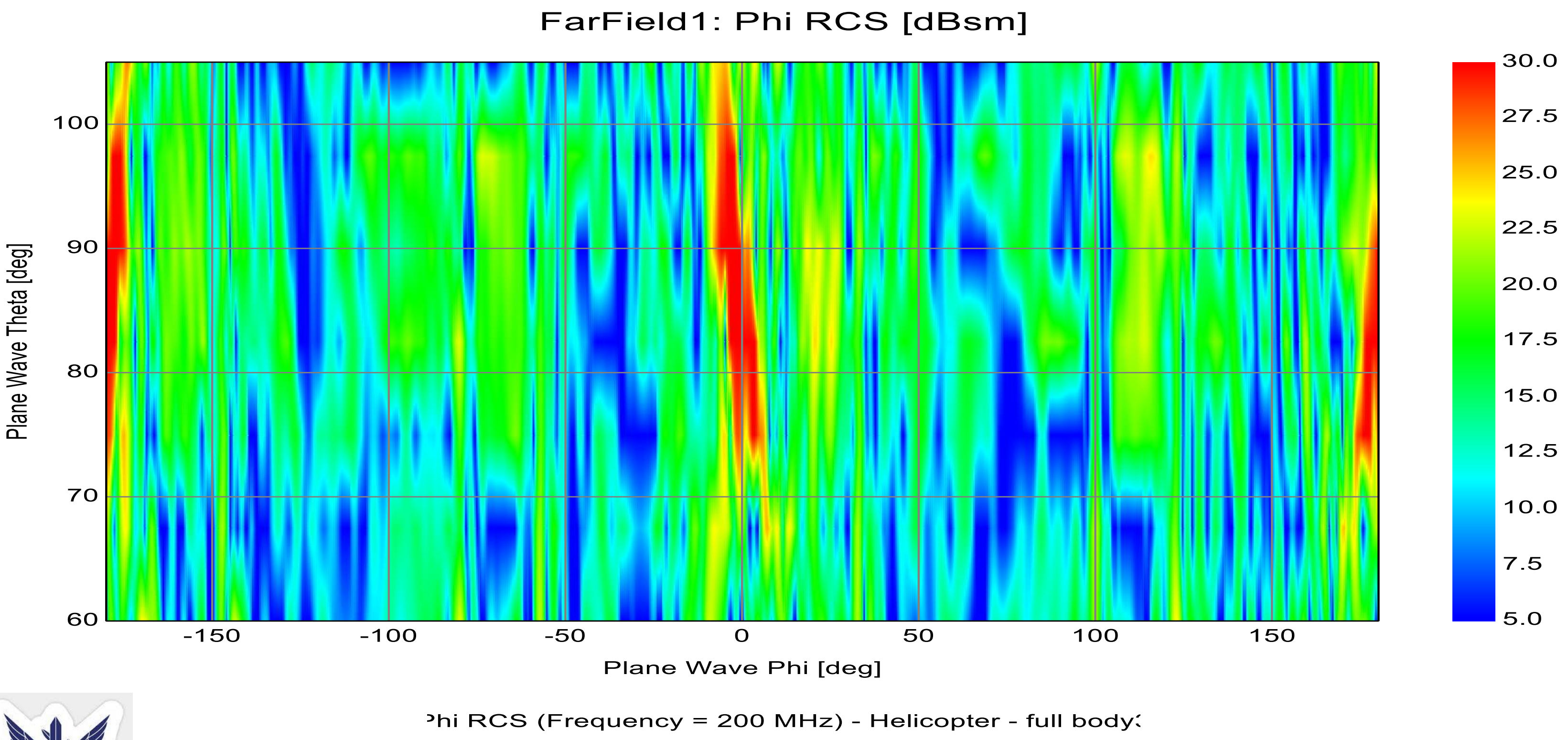
$$\mathrm{E} = A \cdot j$$

  E – the incident field, j – the currents on the mesh, A – the interaction matrix. This equation has the necessary components, but it is j we are after, and not E.
- $j = A^{-1}E$

Helicopter – Feko model



Helicopter RCS



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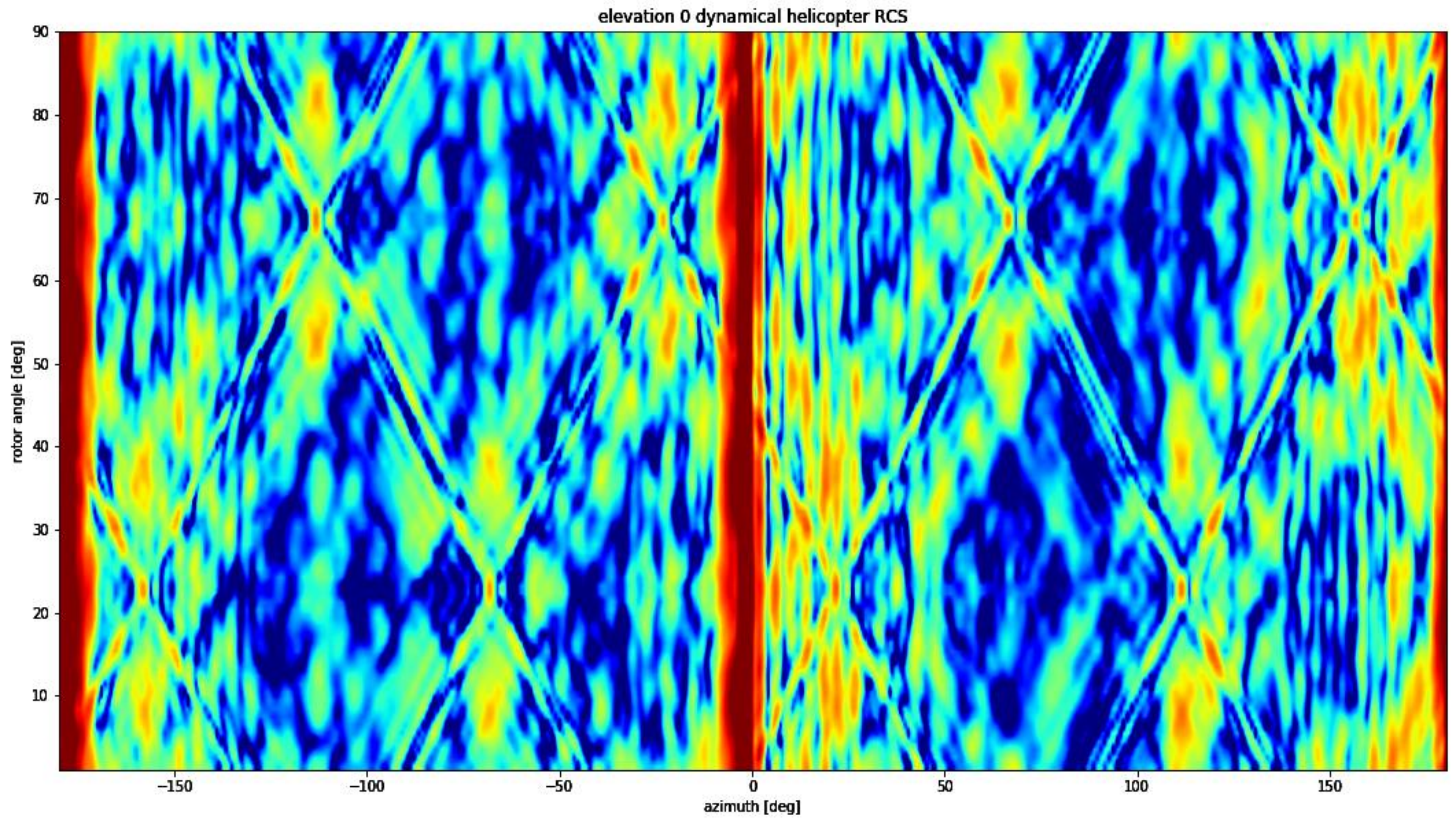
Dynamical RCS

- For a helicopter of constant RPM: $\theta = 2\pi * RPM * t$
- How can we calculate all θ?
  -parameter sweep
  - 

  + for loop.

Dynamic helicopter RCS

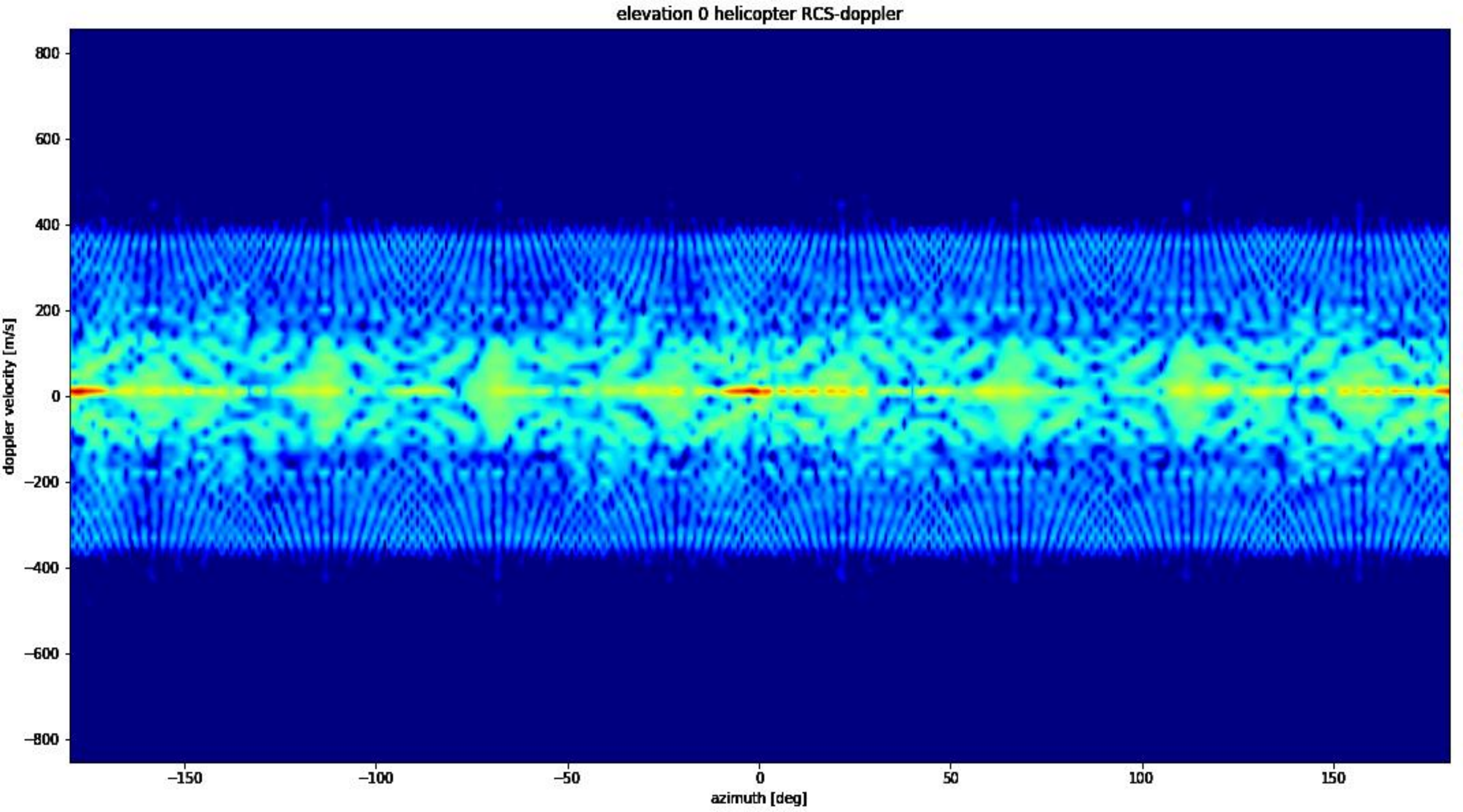

elevation 0 dynamical helicopter RCS
rotor angle [deg]
azimuth [deg]
90
80
70
60
50
40
30
20
10
−150
−100
−50
0
50
100
150

Some fft mathematics

- $T = \frac{1}{4 * RPM} = 39.5ms \to t = \frac{\theta}{90} \cdot T \to \theta(t) = \frac{t}{T} \cdot 90°$
- $\exp\left(2i \cdot \frac{2\pi}{\lambda} v_r t\right) \to$"f"$= \frac{2}{\lambda} v_r$
- $|f_{\max}| = \frac{1}{2\delta t} = \frac{1}{2\left(\frac{\delta\theta}{90}\right)T} \to v_{max} = \frac{\lambda}{4\left(\frac{\delta\theta}{90}\right)T} \approx 850\, m/s$
- For the example radar $t = t_0 + n * PRI, n = 1, \ldots, 32$

$$v_{max} = \frac{\lambda}{4PRI} \approx 600\, m/s$$

$$\delta v = \frac{2 * v_{Max}}{32} \approx 40 m/s$$



elevation 0 helicopter RCS-doppler
doppler velocity [m/s]
800
600
400
200
0
−200
−400
−600
−800
−150
−100
−50
0
50
100
150
azimuth [deg]

Feko is a simulation software; Reference to a measurement

- Doppler spectrum analysis of helicopter for an active seeker head by S. Ahmad and K. A. Ahmad.
- Completely different methods, very similar results. [Feko works]

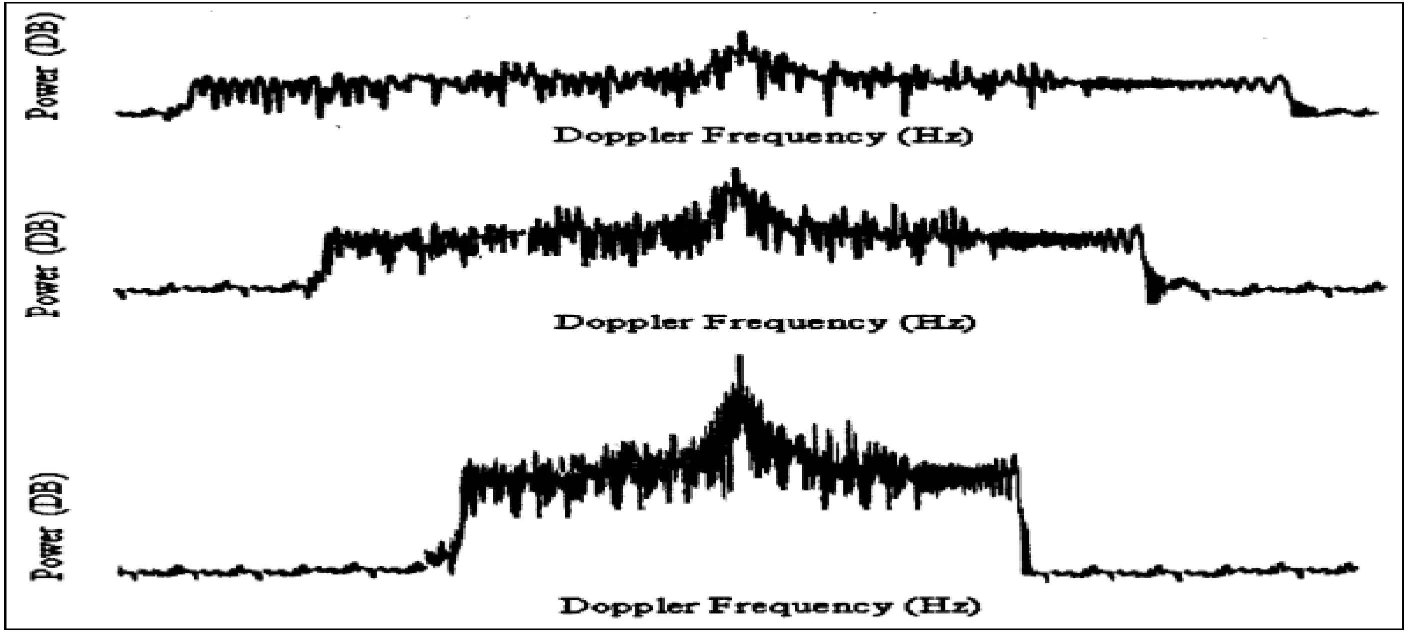
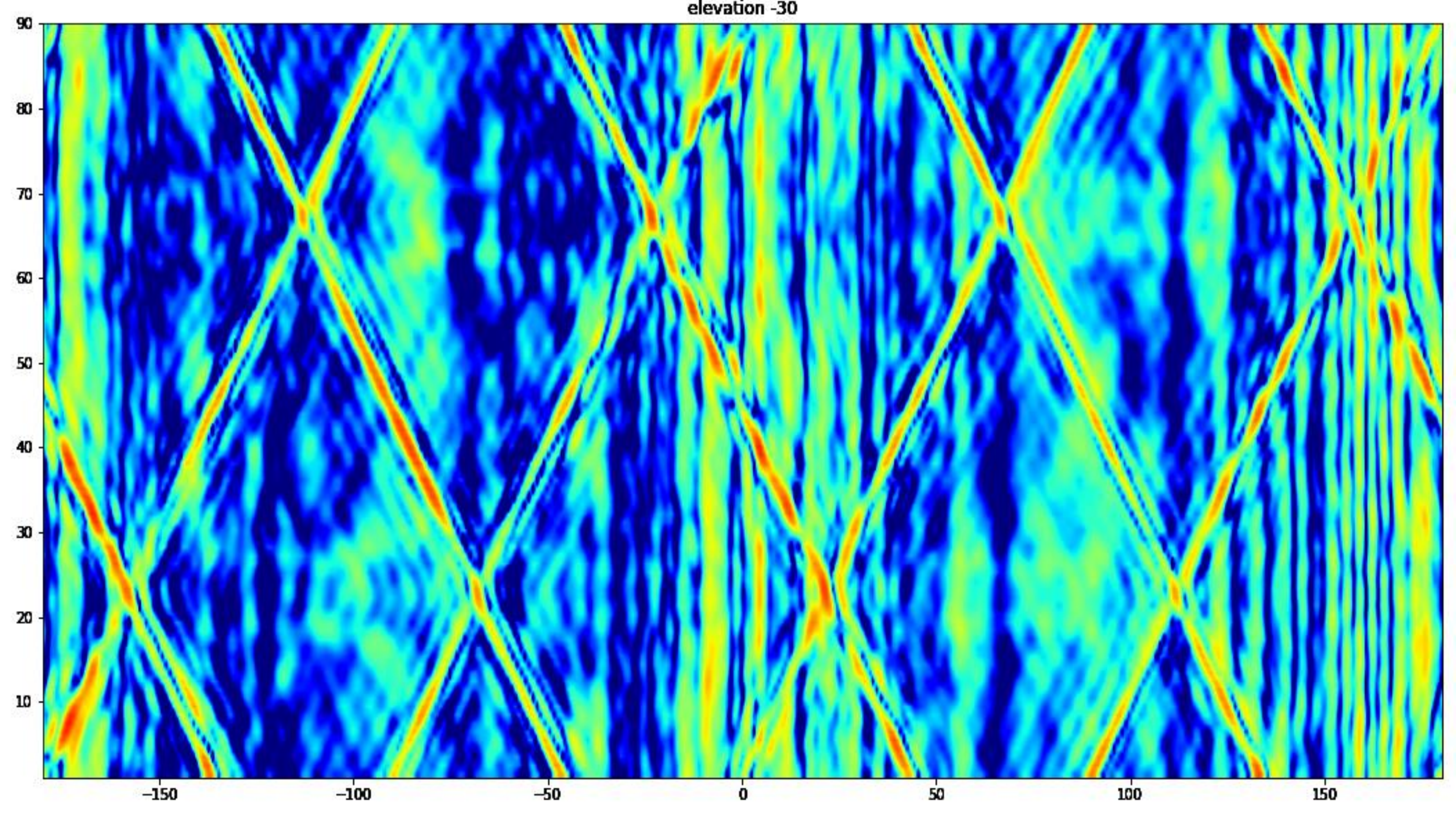
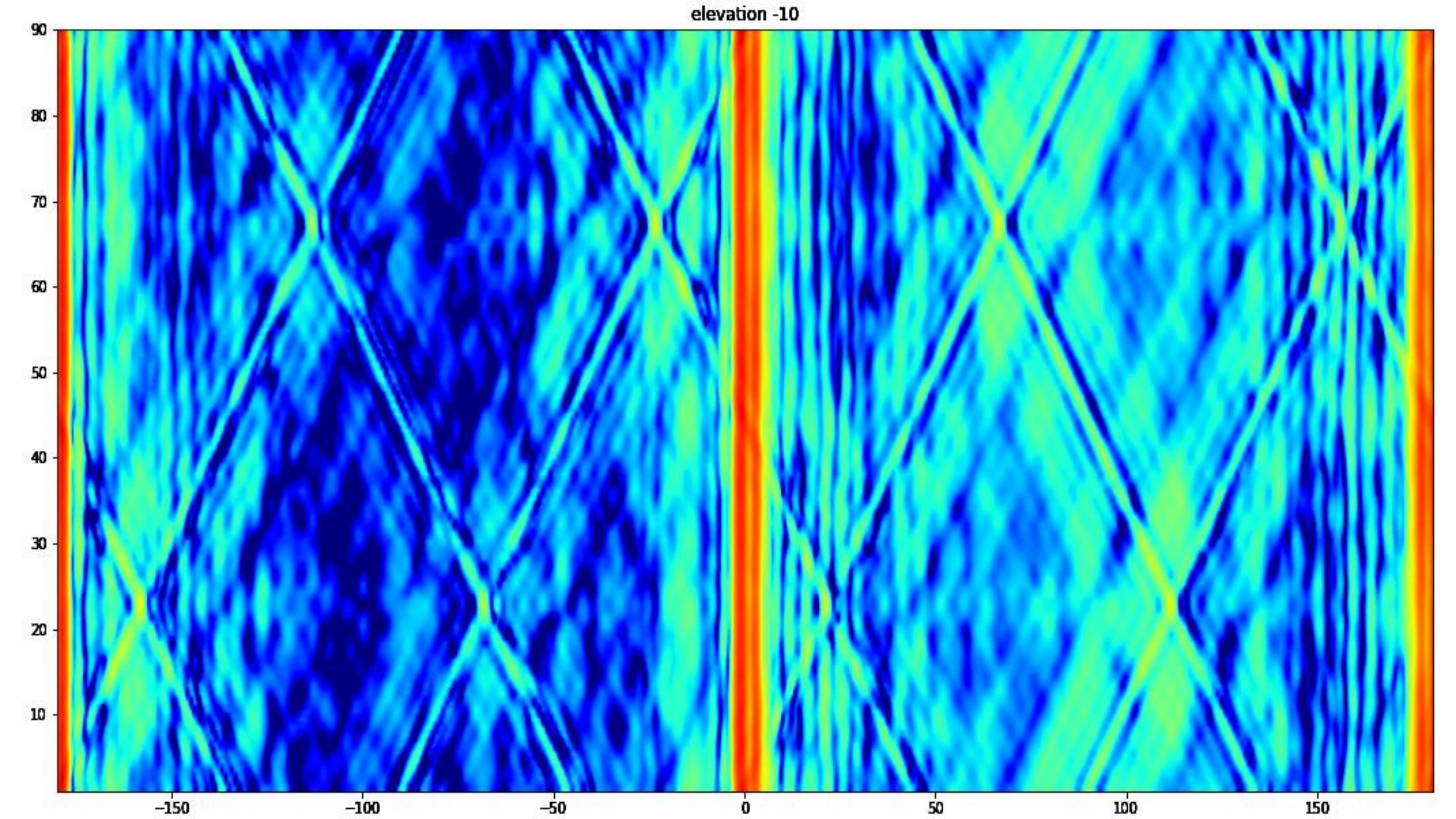
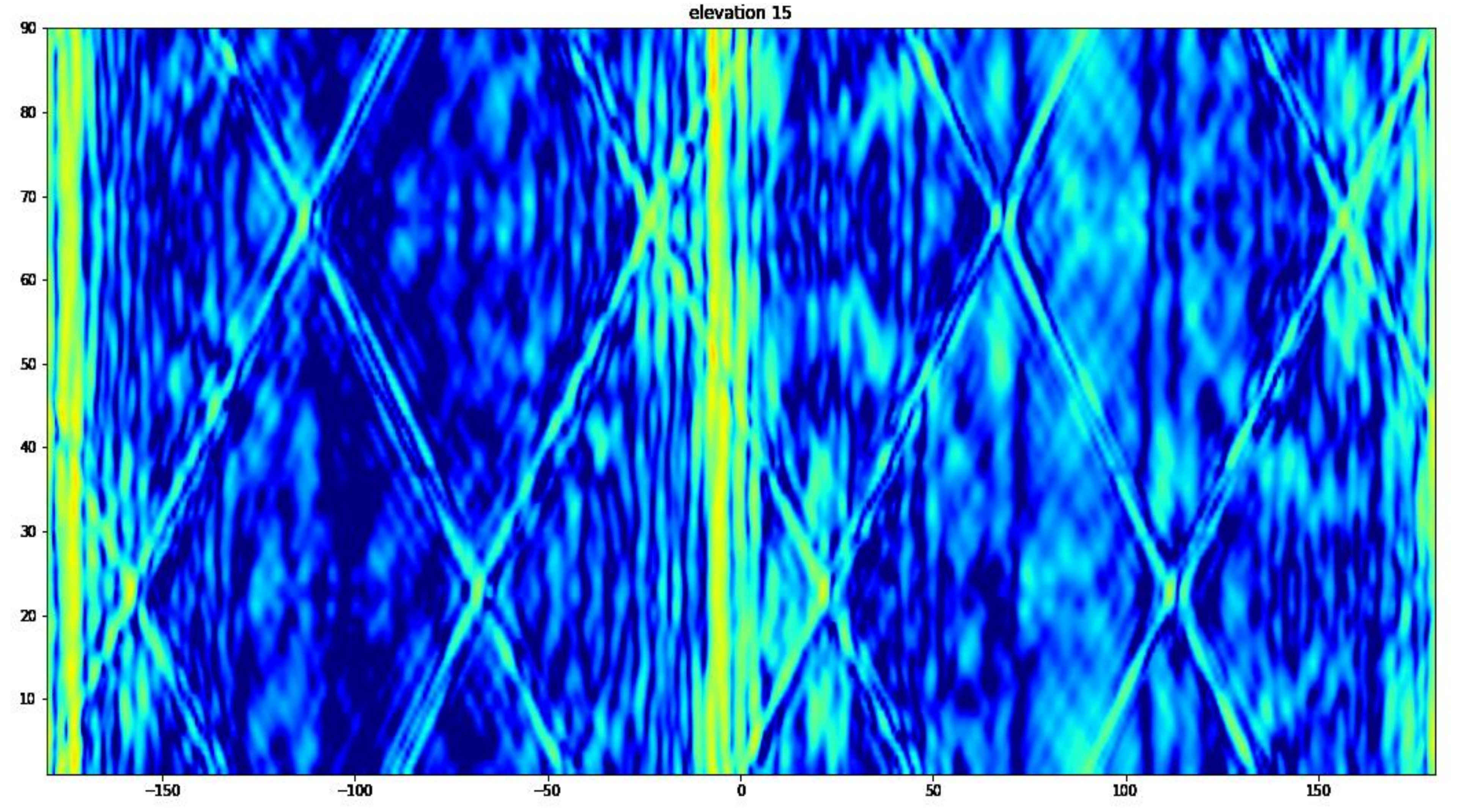


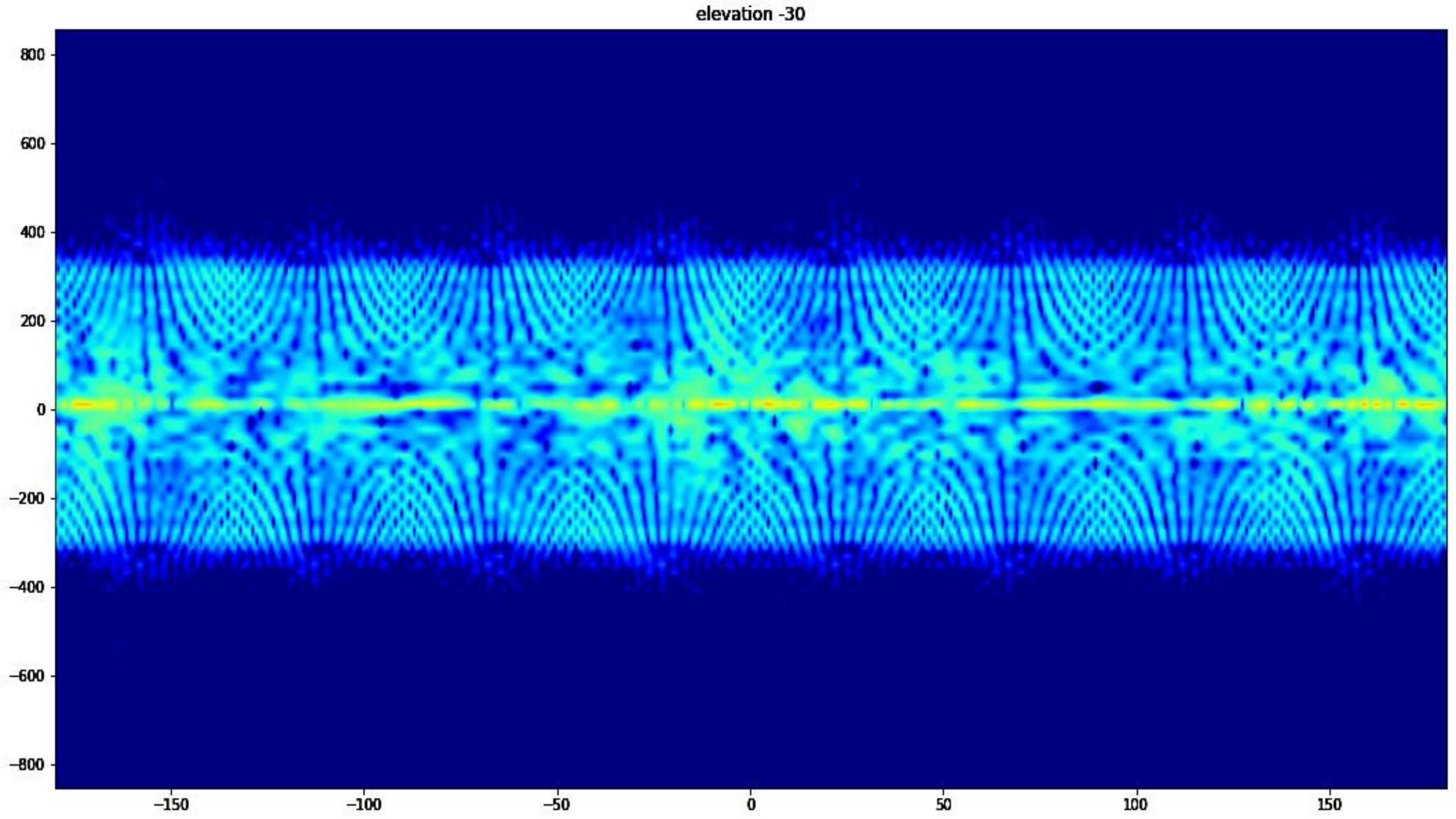
Fig.11. The pulse Doppler spectrum of a helicopter as the angle θ increases

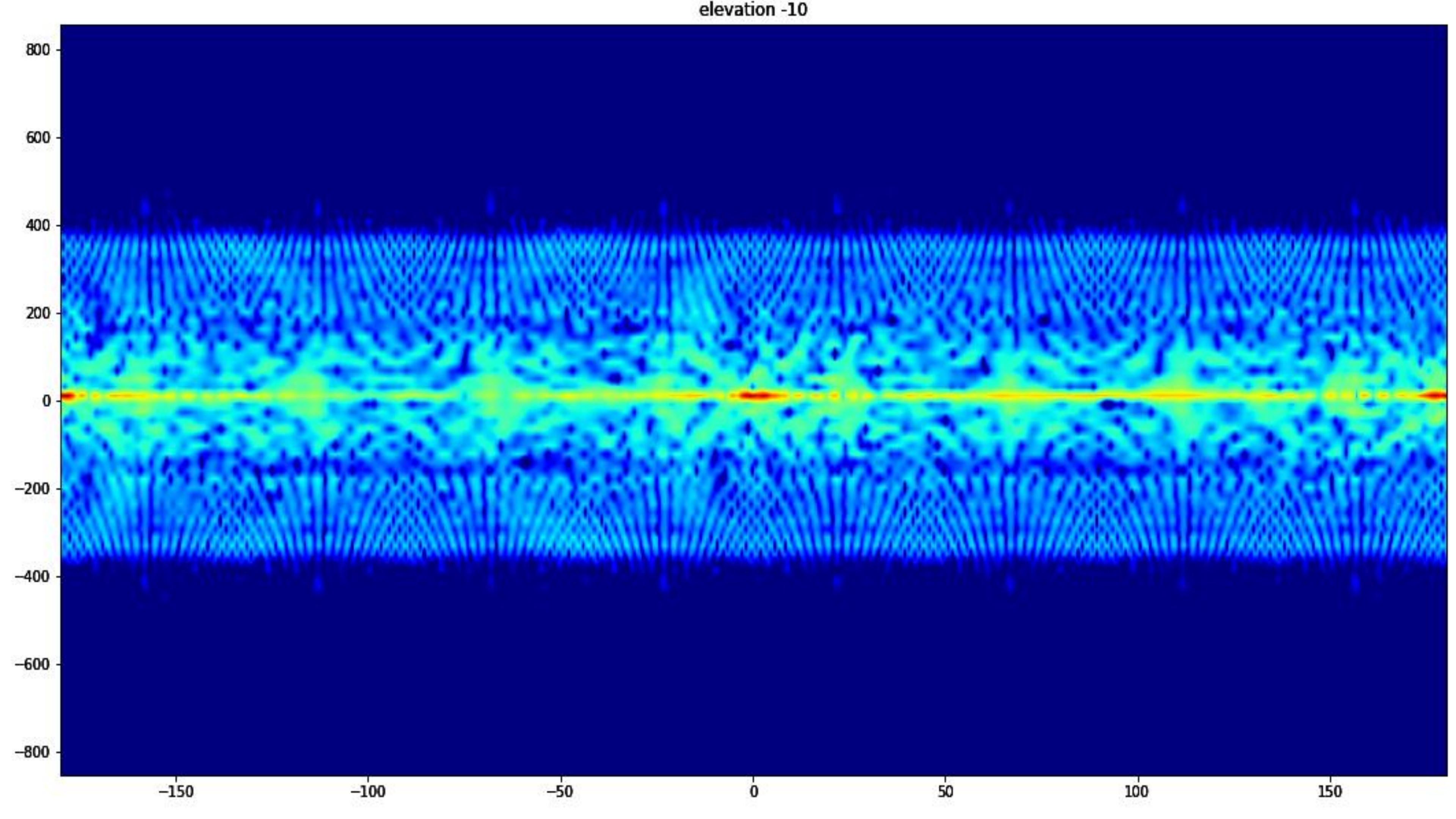


elevation -30
90
80
70
60
50
40
30
20
10
−150
−100
−50
0
50
100
150

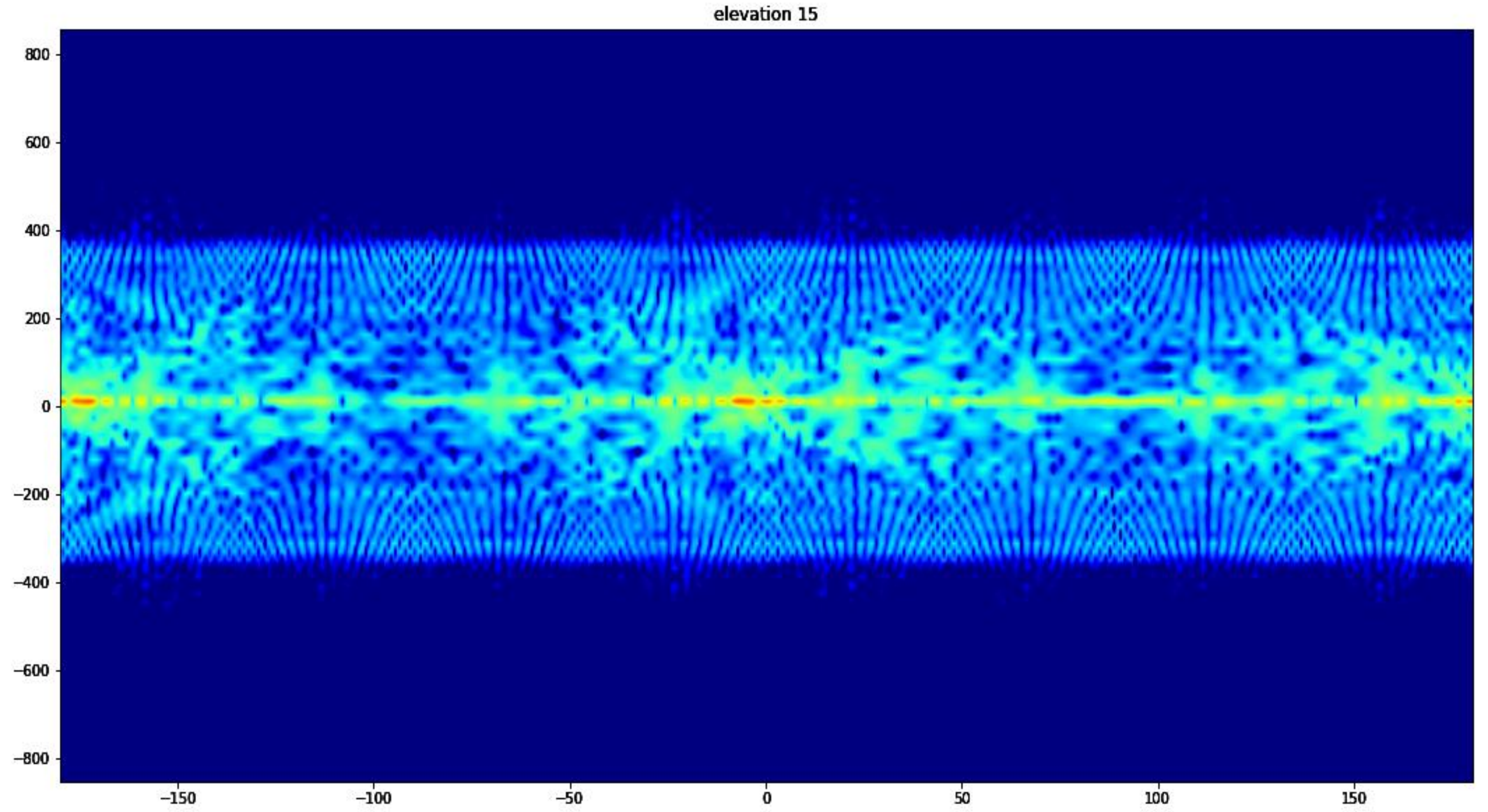

elevation -10
90
80
70
60
50
40
30
20
10
−150
−100
−50
0
50
100
150


elevation 15
90
80
70
60
50
40
30
20
10
−150
−100
−50
0
50
100
150


elevation -30
800
600
400
200
0
-200
-400
-600
-800
-150
-100
-50
0
50
100
150



elevation -10
800
600
400
200
0
−200
−400
−600
−800
−150
−100
−50
0
50
100
150


elevation 15
800
600
400
200
0
−200
−400
−600
−800
−150
−100
−50
0
50
100
150

A useful trick

- We had to calculate $\sigma(\theta)$.
- The RCS is calculated by inverting the interaction matrix.
  The currents produce the scattered field.
- Lets looks at a partitioned interaction matrix:

$$\begin{pmatrix} body & body \rightarrow rotor \\ rotor \rightarrow body & rotor \end{pmatrix} \cdot \begin{pmatrix} j_{body} \\ j_{rotor} \end{pmatrix} = \begin{pmatrix} E_1 \\ E_2 \end{pmatrix}$$

- Some of the matrix is θ independent!

Numerical Green Function

- We can store the “body” but we actually need “body”$^{-1}$.
- If “body” holds much more elements than “rotor”, the complexity decreases.
- Body can be calculated on its own using symmetries.
- Possible uses:
  helicopter
  antenna placement
  multiple configuration platform

Questions?