Progress in low-boom research

- Considerable progress in understanding, simulating, shaping sonic booms
- NASA planning tests with Lockheed-Martin low-boom flight demonstrator in early 2020s
- Sonic-boom loudness standards earliest in the mid-2020s

Formidable challenges remaining:
- Acceleration/deceleration booms
- Indoor booms
- Off-track booms
- Atmospheric variability
- “Low boom, high drag” paradox
- Public acceptance

- What if overland flight bans do not get lifted, or if loudness standards cannot be met in the foreseeable future?
Near-term solution: Supersonic flight routing over water

- Supersonic over water, subsonic over land
- Doable under current laws
- Trade on flight time & fuel
- Intra-continental, coast-to-coast flights possible with Mach cutoff

- Rerouting approach easily implementable; in effect with Concorde

- Required distance between flight paths and shores to avoid sonic boom landfall?
Solution: Simulation/computation of the sonic boom carpet

Theory and modeling of sonic boom propagation (1)

- Flight faster than Mach 1 produces shock waves propagating at the speed of sound
- On the way down, shock waves are gradually bent upward due to rising temperatures
- Shock waves reach ground only inside a “sonic boom carpet” of certain width

- Sound-bending governed by Snell’s law, similar to light passing through media
- Here: atmospheric layers of different temperatures and different speeds of sound

\[
\frac{c_1}{\cos \theta_1} + u_1 = \frac{c_2}{\cos \theta_2} + u_2
\]

\(c_i\): speed of sound
\(\theta_i\): sonic ray angle
\(u_i\): horizontal wind speeds

Sonic boom rays and carpet [from D. Coulouvrat, modified]
Solution: Simulation/computation of the sonic boom carpet

Theory and modeling of sonic boom propagation (2)

- Modeling of sonic boom propagation possible with well-established geometrical acoustics method of *sonic ray tracing*
- Following the path of one point on the shock wave front over time (*ray*)
- Basic equations known since 70s (Onyeonwu, and others); inputs: Mach number, wind vector, temperature, ray emission angle
- Plotkin, Page, and Haering laid down equations for ray tracing in ellipsoidal earth and 3-D atmosphere
- Relevant for long propagation distances
- Implemented in NASA’s PCBoom
Implementation of sonic boom carpet computation

- Core: proprietary code for 3-D sonic ray tracing in arbitrary atmosphere
- Similar to ray tracing in NASA’s well-established PCBoom (solutions match closely); yet stopping short of computing boom signatures and loudnesses
- Sonic rays emitted downward from aircraft trajectory in varying angles and traced on their way through the atmosphere
- Carpet edges constituted by points of impingement of starboard/port marginal rays
- Repeated for numerous trajectory positions; impingement points delimit boom carpet

Example of sonic ray tracing in a certain atmosphere for determining boom carpet width.
Left: Frontal view; marginal rays as bold lines. Right: 3-D view (ground-reaching rays only).
NB: strong crosswinds, ray curvature depending on temperature gradients.
Process chain of supersonic flight route design and optimization

A. Flight path drafting
B. Mission simulation
C. Boom carpet computation

Coastline buffer barely satisfied?

yes

Optimal route found

no

A2. Flight path adaptation
Supersonic flight route design chain (1): Flight path drafting

**Platform: Google Earth**

1) Draw great circle connection between origin and destination (red) as a reference
2) Manually plot flight tracks with Path tool (green)
   - Keep preliminary distance to shores
   - Trade between detour (minimize) and supersonic share (maximize)
   - Take turn radii into account
   - Take settlements into account for overland corridors
3) Export .kml file with subsonic segments encoded

*Drafted flight route for London-Jeddah*
Supersonic flight route design chain (2): Mission simulation

- Proprietary mission simulation tool SuperTraC (supersonic trajectory calculator)
- Inputs: flight path from Google Earth; vehicle specifications (masses, speeds, engine maps, aero maps, ...); airport data; atmospheric data (density, pressure, temp., winds)
- Output: flight trajectory (distance, speed, position, time, fuel consumption)
- Mach cutoff flight optional

London-Jeddah trajectory with Mach cutoff overland flight.
HISAC-A supersonic business jet, atmosphere of 2015-01-01 at 06:00 hours.
Supersonic flight route design chain (3): Sonic boom carpet computation

- Sonic ray tracing for calculated flight trajectory, using the same atmosphere as for mission simulation

- **Carpet infringes numerous coast lines**
- **Accelerations and decelerations late**

*Sonic boom carpet (white) for calculated preliminary flight trajectory. Atmosphere of 2015-01-01 at 06:00 hours.*
Supersonic flight route design chain (4): Adaptation and iteration

Flight route adaptation, mission simulation, carpet computation; iterate till satisfaction
Robust flight routing

- Tremendous effect of atmospheric variability on sonic boom carpets
- Coincidentally, benign atmospheric conditions often available
- Suggestion: development of flight paths viable for a reasonable share of atmospheric conditions by considering large atmospheric databases
- Inferring a flight time penalty to optimum route, yet sparing repeated route optimization

All-year of 2015 sonic boom carpets on the optimized London-Jeddah route.
Conclusion and Outlook

- Methodology for supersonic flight route design by considering sonic boom carpets
- Basic assumption and approach: sonic booms not allowed to touch land
  - Flight paths over water, boom carpet not to infringe coast lines
- Flight route design chain: manual flight path drafting, automated mission simulation, automated sonic boom carpet calculation, iteratively
- Discretized atmospheric data implemented to account for atmospheric variability
- Option of Mach cutoff overland flight implemented

- Flight path adaptation to be automated
  - Goal of fully automatic flight path design
- Implementation of topography, aimed at adaptive sonic boom cutoff altitude
Thank you for your attention!

bernd.liebhardt@dlr.de

Relevant publications

Estimation of the Market Potential for Supersonic Airliners... [AIAA 2011-6808]
Analysis of the Market Environment for Supersonic Business Jets [DLRK 2011]
Supersonic Deviations – Assessment of Sonic-Boom-Restricted Flight Routing [JoA 51(6) 1987-95, 2014]
Small Supersonic Airliners – A Business Case Study Based on the Aerion AS2 Jet [AIAA 2017-3588, 2017]
Discussion (1): Automatization of flight route design chain

1) Flight path drafting
   - Done manually; difficult to automatize; at least initial solution necessary

2) Mission performance simulation
   - Automated

3) Sonic boom carpet computation
   - Automated

4) Flight path adaptation w.r.t. boom carpet violations
   - Difficult, but possible to automat

- *Fully automated design chain tangible, save for initial flight path*
  (available from proprietary flight path database)
Discussion (2): Evanescent waves

- Sonic booms audible beyond cutoff through creeping/evanescent waves
- NASA FaINT project (incl. flight tests): considerable sound events recorded beyond lateral as well as altitudinal cutoff points
- Reliance on exact cutoff points insufficient.

Possible relief:
1) Sophisticated noise propagation model for the shadow zone
2) Buffer zones
Ray tracing on ellipsoidal earth.

Solution: Ray tracing in *ellipsoidal Earth* and in atmospheres with *vertical winds*.

Runaway rays disappear.

Ray tracing results verified using NASA’s PCBoom.