Supersonic Flight Routing by Sonic Boom Carpet Simulation

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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

NAXA X-59 QueSST

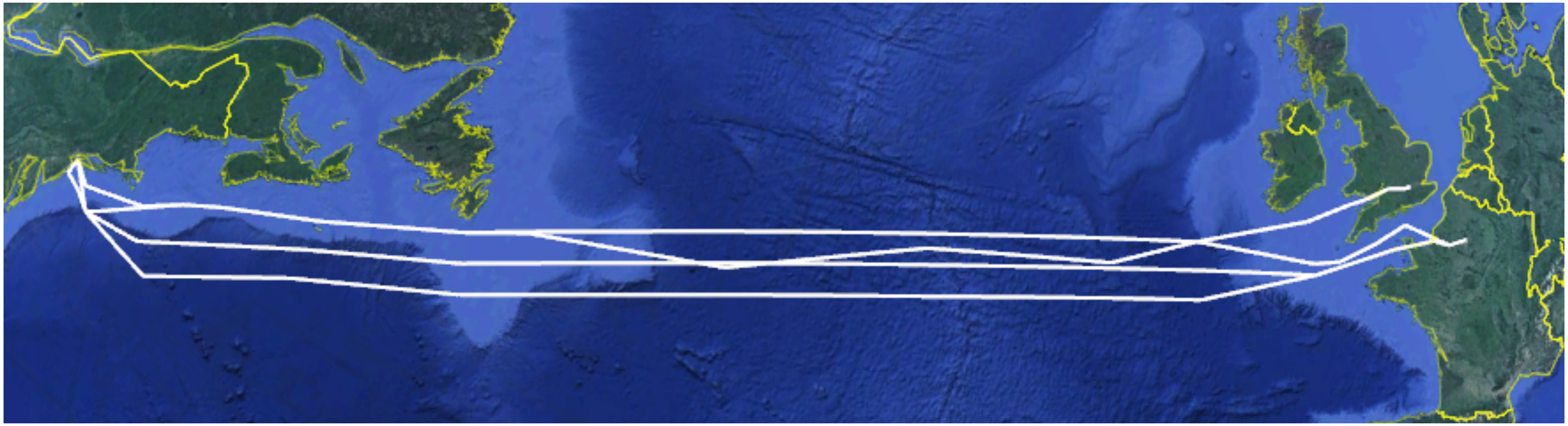
- *What if overland flight bans do not get lifted, or if loudness standards cannot be met in the foreseeable future?*

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?*



Transatlantic Concorde routes

Solution: Simulation/computation of the sonic boom carpet

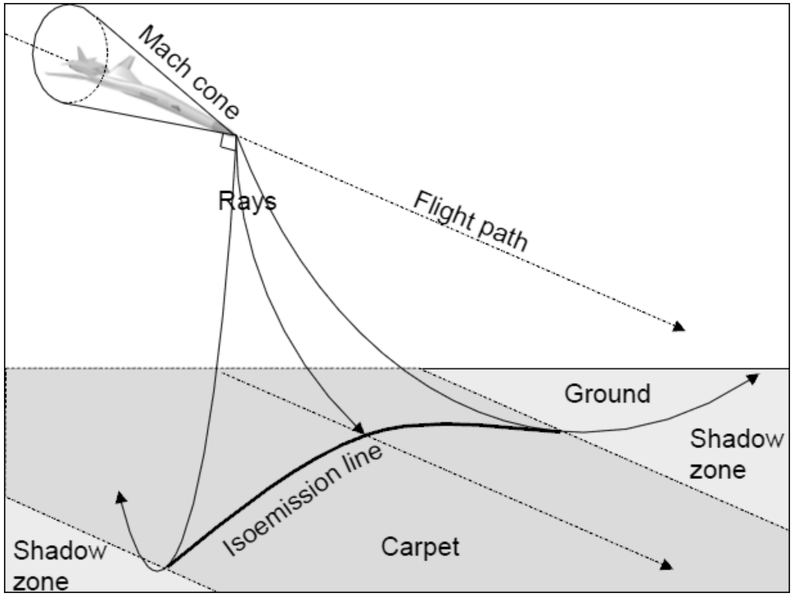
Theory and modeling of sonic boom propagation (1)

- 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
θ_i: sonic ray angle
u_i: horizontal wind speeds

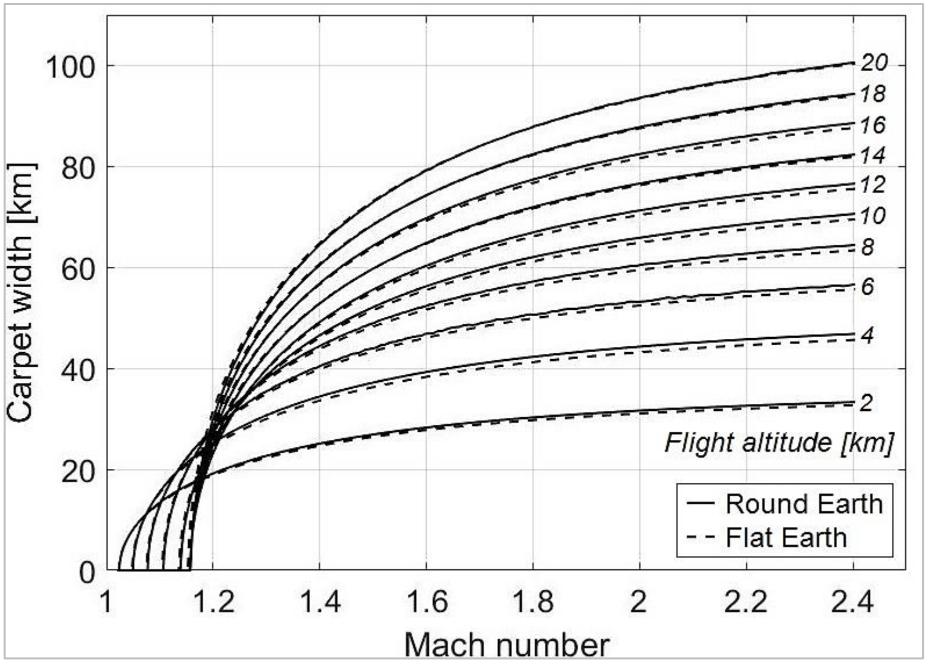


Sonic boom rays and carpet [from D. Coulouvrat, modified]

Solution: Simulation/computation of the sonic boom carpet

Theory and modeling of sonic boom propagation (2)

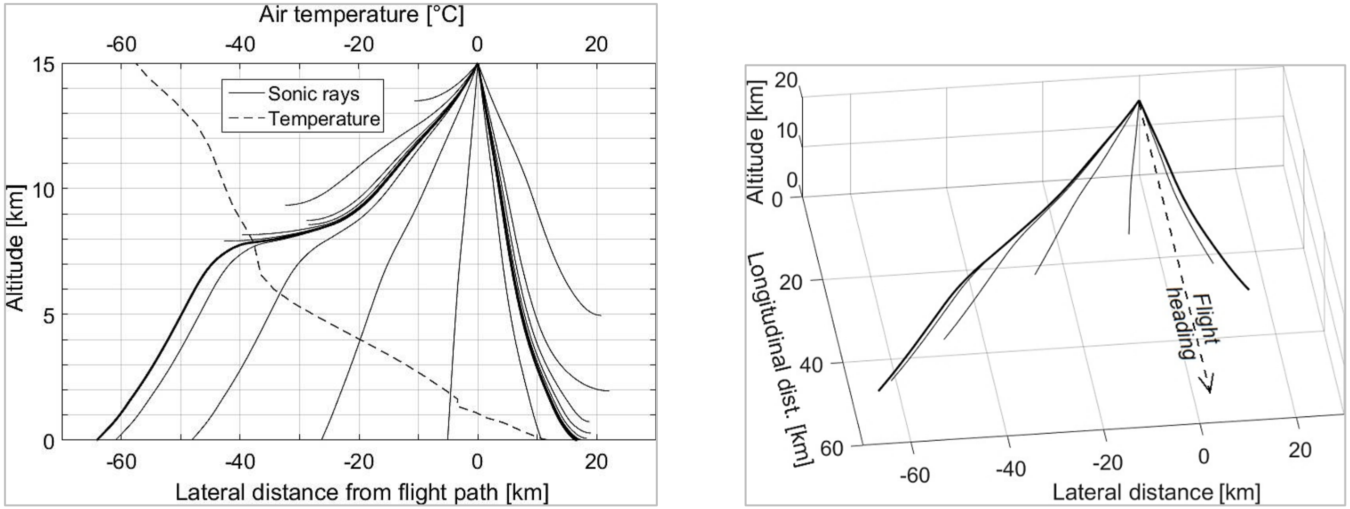
- Modeling of sonic boom propagation possible with well-established geometrical acoustics method of *sonic ray tracing*
- Following the path of one point on the shock wave front over time *(ray)*
- Basic equations known since 70s (Onyeonwu, and others); inputs: Mach number, wind vector, temperature, 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



Theoretical sonic boom carpet widths

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.

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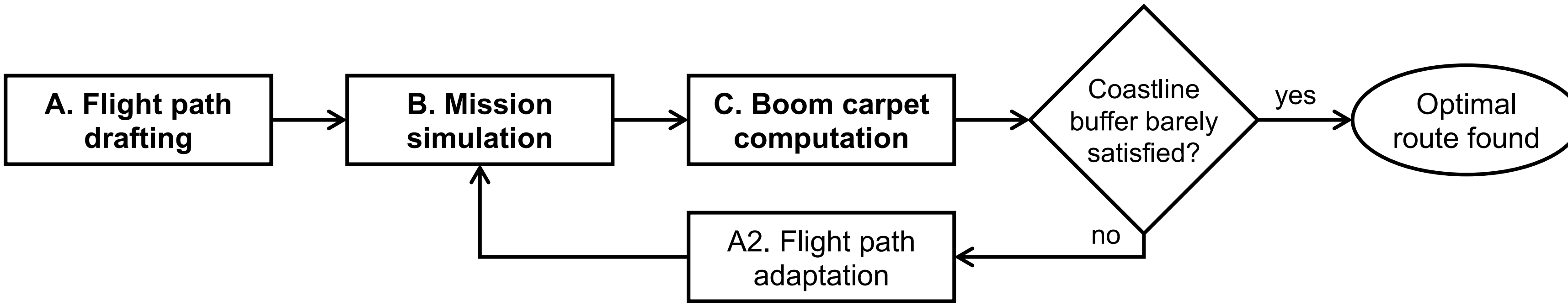
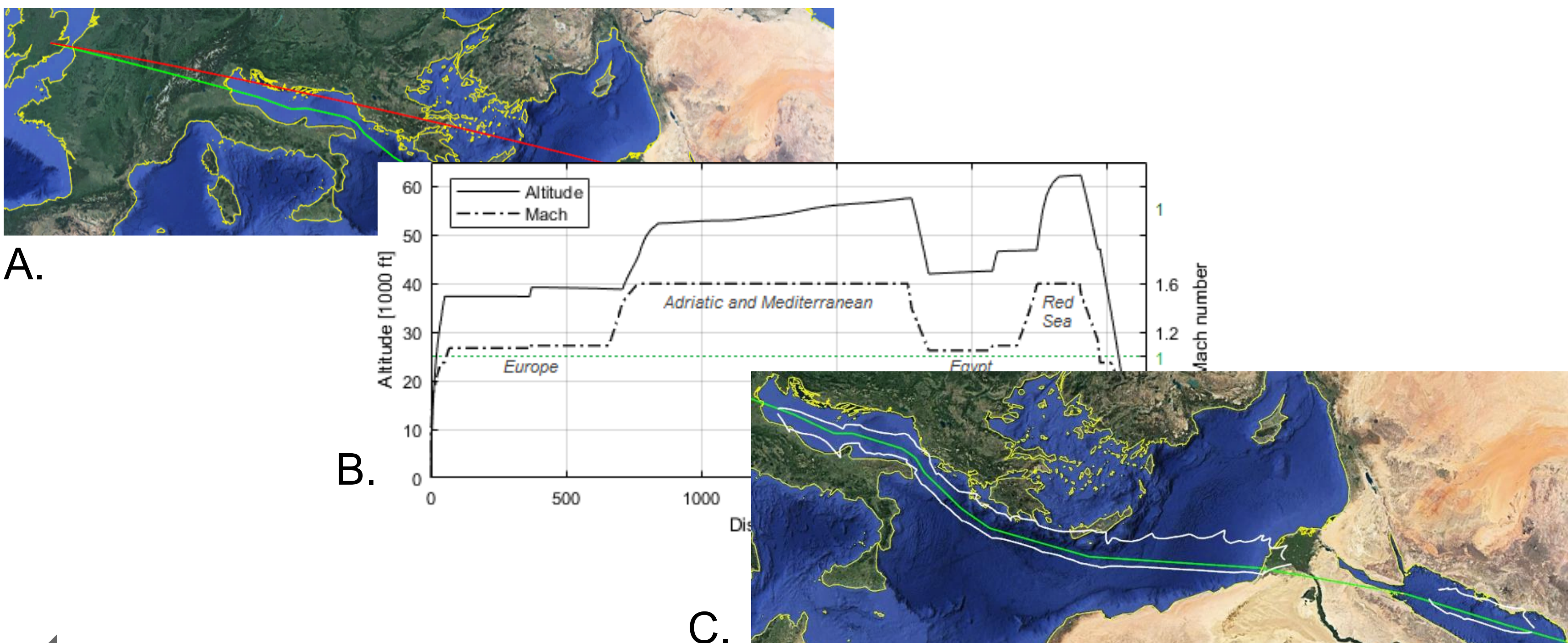
Process chain of supersonic flight route design and optimization





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

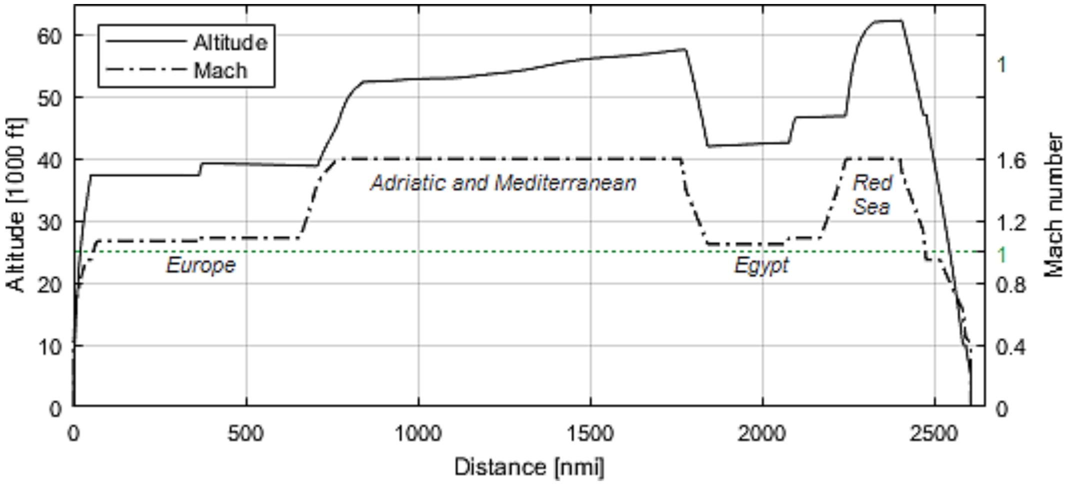
Platform: Google Earth

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

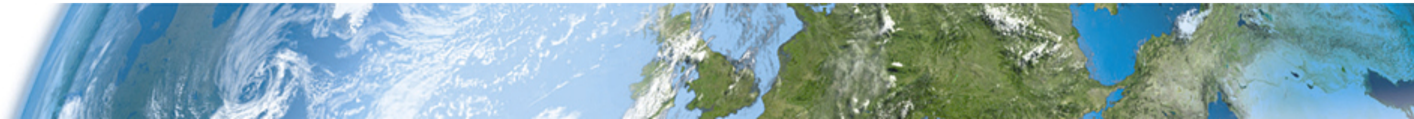
Drafted flight route for London-Jeddah

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.



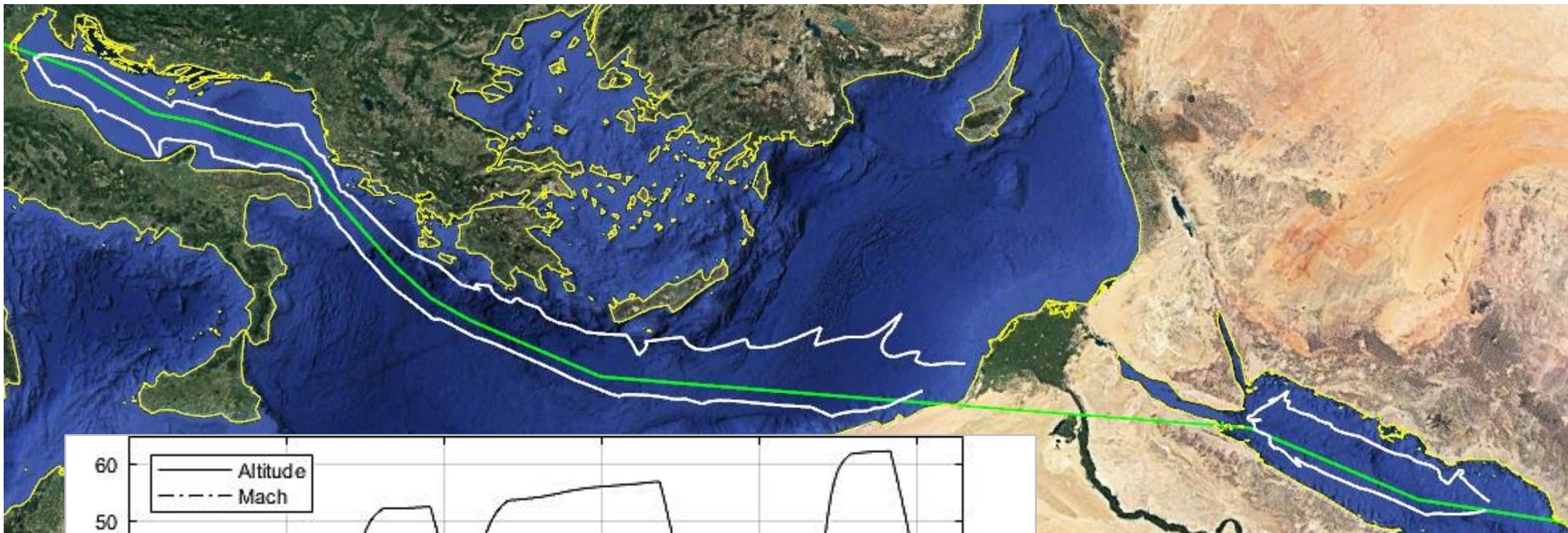
Supersonic flight route design chain (3): Sonic boom carpet computation

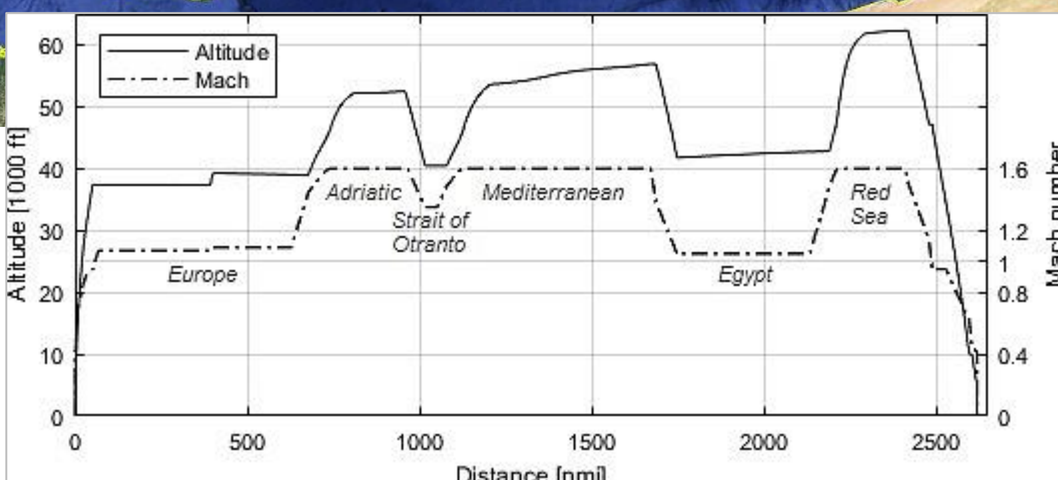
- Sonic ray tracing for calculated flight trajectory, using the same atmosphere as for mission simulation
  - *Carpet infringes numerous coast lines*
  - *Accelerations and decelerations late*

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

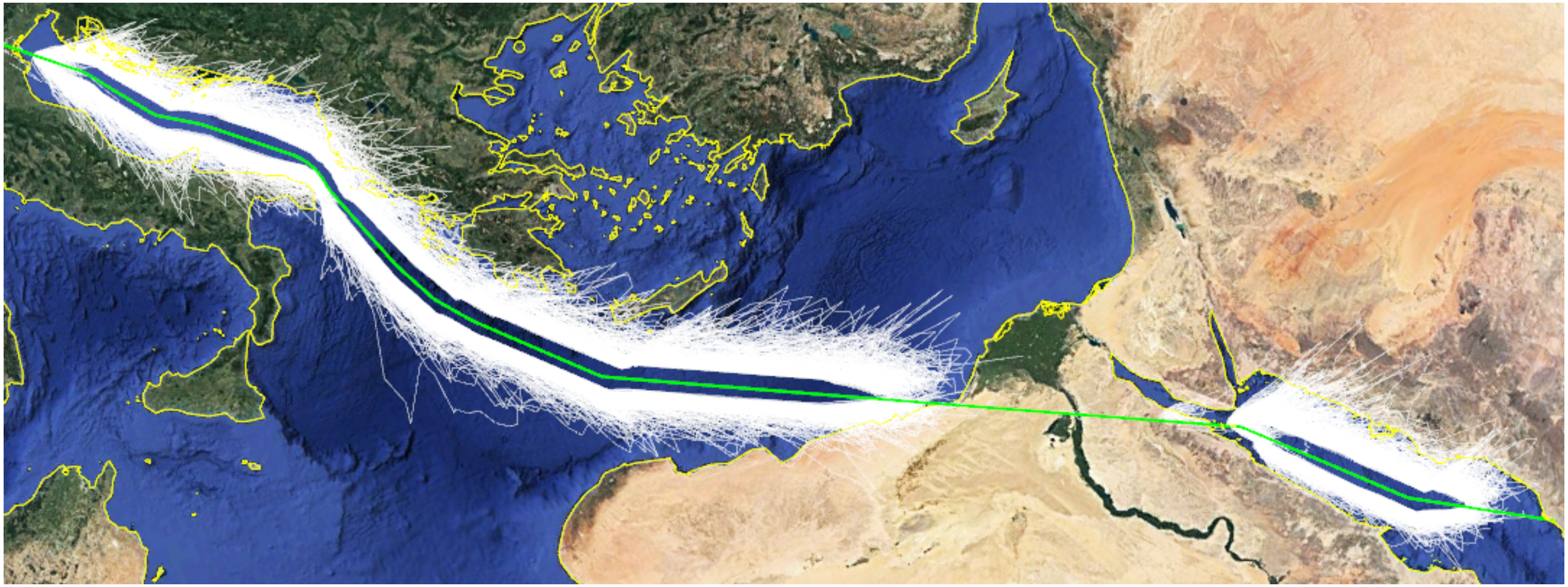




Final sonic boom carpet and corresponding trajectory.

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.

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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!

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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]

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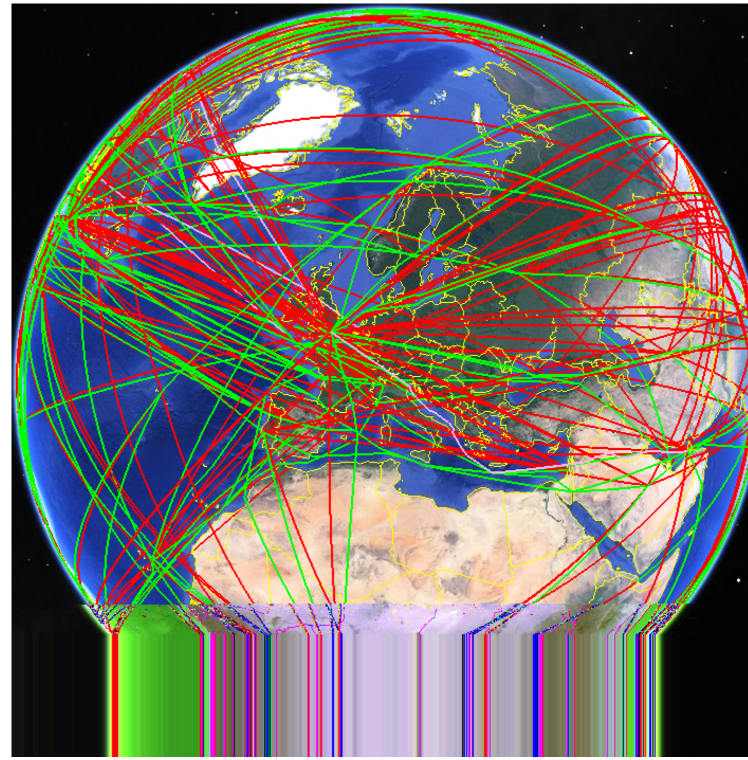
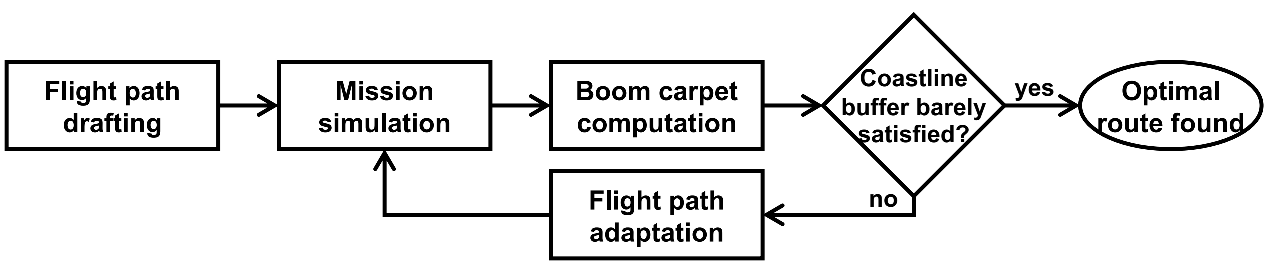
Discussion (1): Automatization of flight route design chain

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)

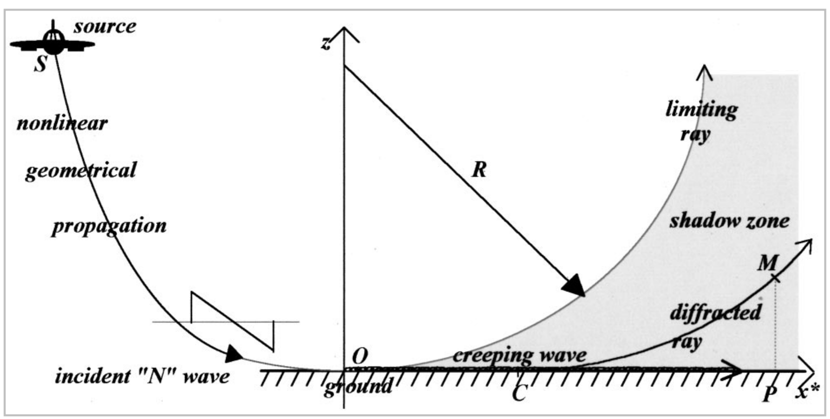


Discussion (2): Evanescent waves

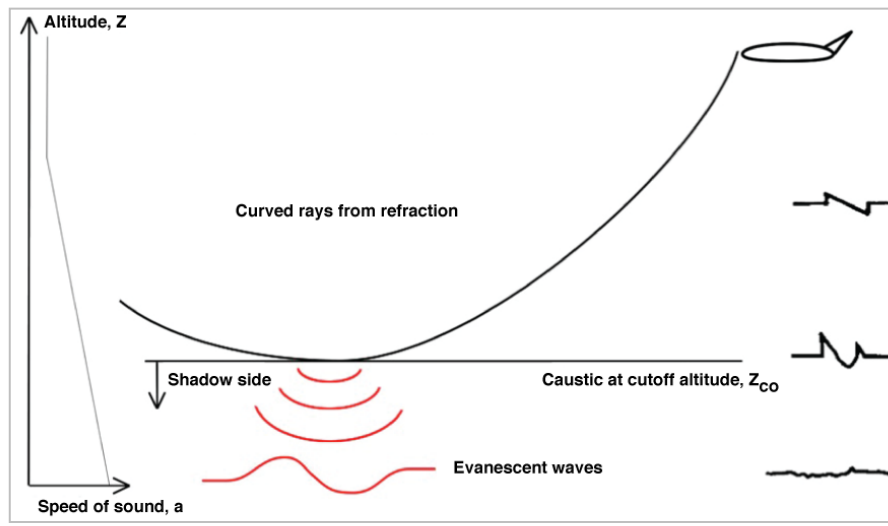
- Sonic booms audible beyond cutoff through creeping/evanescent waves
- NASA FaINT project (incl. flight tests): considerable sound events recorded beyond lateral as well as altitudinal cutoff points
- *Reliance on exact cutoff points insufficient.*

Possible relief:

1) Sophisticated noise propagation model for the shadow zone
2) Buffer zones



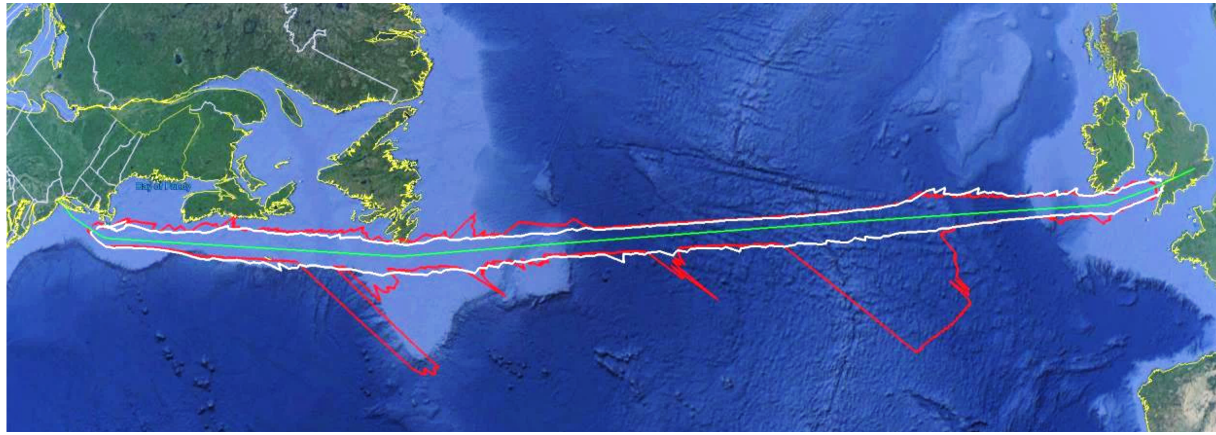
Lateral shadow zone [Coulouvrat, CNRS, 2002]



Altitudinal shadow zone [Cliatt et al., NASA, 2016]

Ray tracing on ellipsoidal earth. Ray tracing verification.

- Solution: Ray tracing in *ellipsoidal Earth* and in atmospheres with *vertical winds*
- Runaway rays disappear



- Ray tracing results verified using NASA's PCBoom