FL/GHTKEYS

DUST ECONOMICS

**Cost-based approach
to flight operation in contaminated air**

Entering ash clouds can be costly

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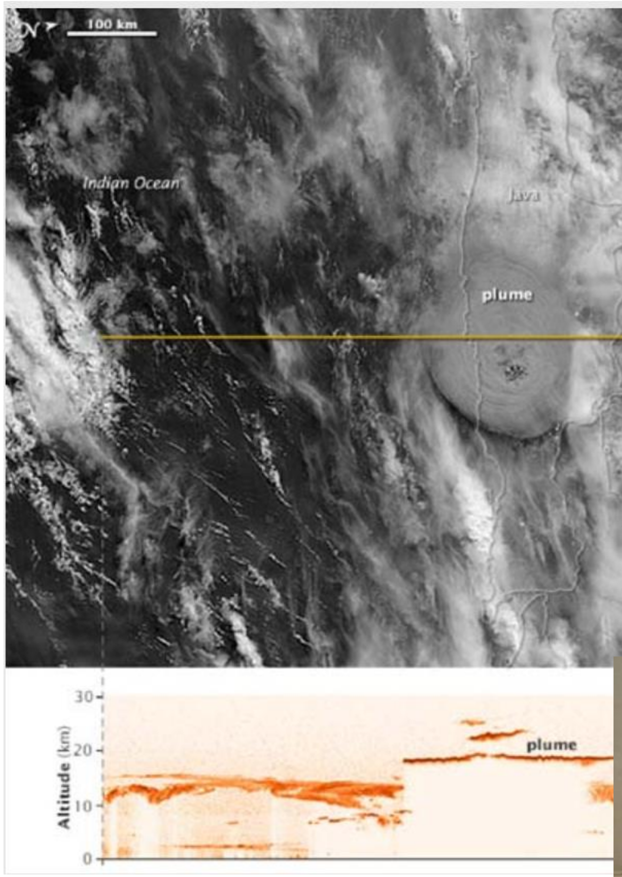
Kelut (Indonesia) ash encounter 14 February 2014:

- A320 unexpectedly enters volcanic ash plume
- ca 8 minutes of exposure
- no abnormal engine indications
- Safe landing in Jakarta
- Engine inspection:
  - Evidence of ash deposit in combustor and HP turbine
  - Engines removed for strip and repair



Estimated cost: several million USD

Avoiding ash clouds can be costly, too

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2010 eruptions of Eyjafjallajökull:

- Closing EU airspace for 6 days
- Ca 100.000 flights cancelled
- Estimated cost: 1.3 billion €

Balanced Approach: Cost-based

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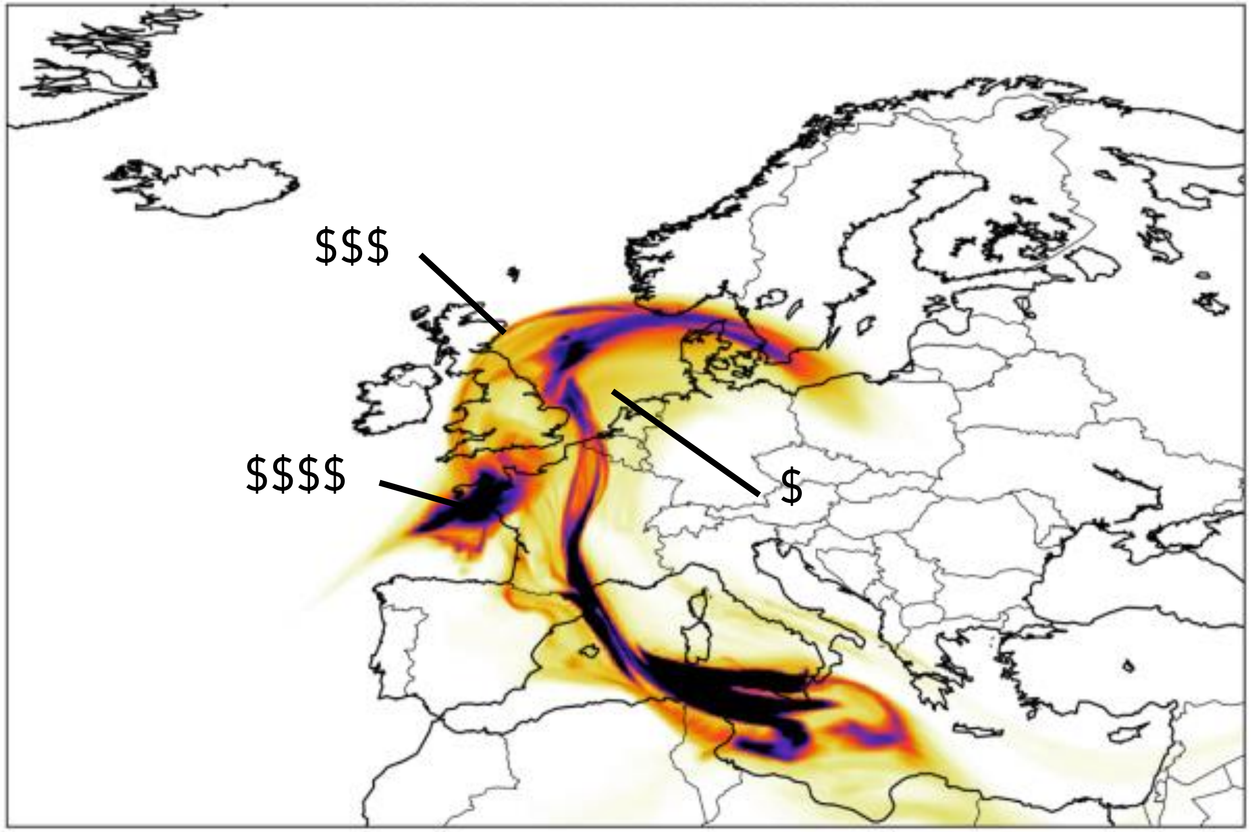
FLIGHTKEYS found a way to add „price tags“ to ash clouds



Latest studies and developments show that cost-based ash-cloud avoidance is feasible and much more efficient than strict avoidance.

Flight operations through contaminated air

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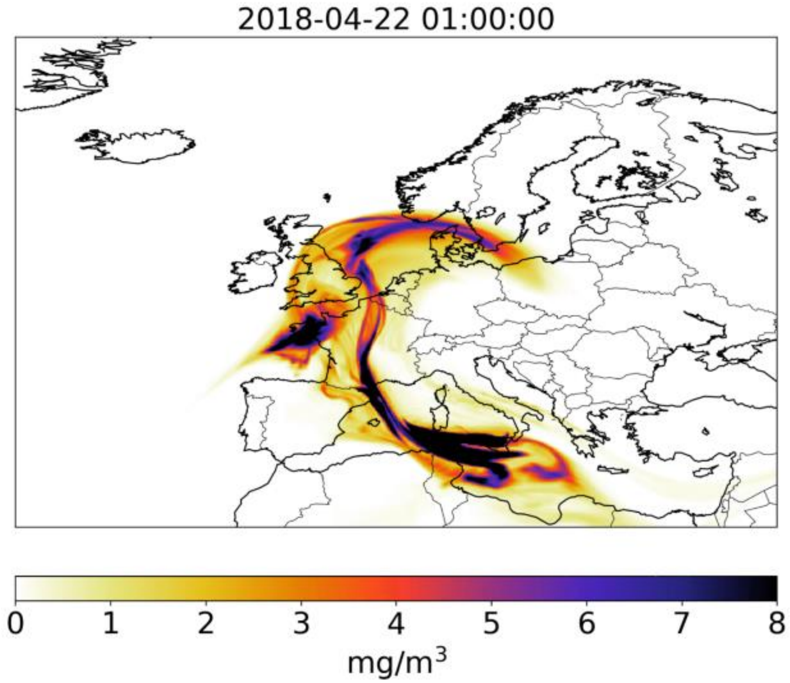
Recent studies show (Clarkson, Rolls-Royce):

- Flight through contaminated air is not a safety risk, but rather a matter of increased cost in most cases.
- Only very few small areas require strict avoidance.
- Modern jet engines are sensitive even to low levels of air contamination, well below the safety limits defined by regulators and risk management strategies implemented by airlines

Solution by FLIGHTKEYS (demonstrated in EUNADICS-AV project 2019):

- To minimize the economic impact and continue safe and economic operation in volcanic ash release events, the methods presented here will allow full integration into state-of-the-art trajectory optimizer systems.
- The basic concept of this method is to project future cost onto contamination-exposed trajectory segments. The following slides describe the basic assumptions and conclusions that form this method.



Engine Contamination and Effects

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Contaminants:

- Sand / dust
- Volcanic ash
- Sulphur oxides
- Ice crystals

Primary Damage:

Self-repairing
    Material deposition in compressor and turbine
Irrecoverable
    Compressor erosion – aerofoils and rotor tips
    Turbine erosion

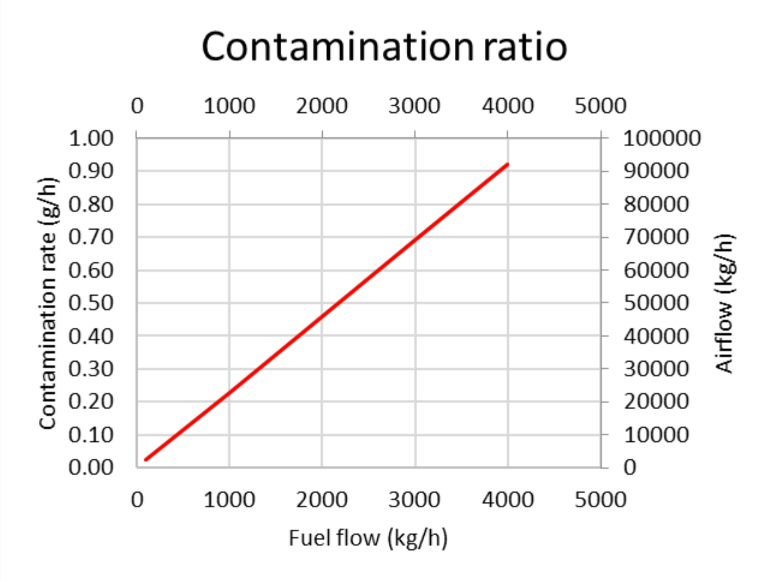
Secondary Effects:

1. Fuel consumption increase
2. Lifetime reduction (reduced time on wing)

Assumption 1

Mass of ingested contaminant is proportional to Fuel Flow

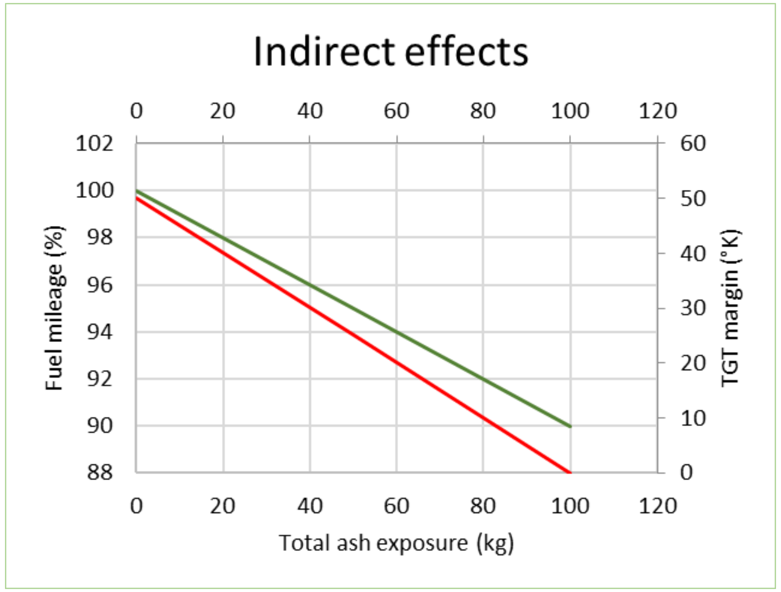
- We assume that air ingested into the engine core is determined by a fixed air/fuel ratio, thus in effect linking contaminant ingested into the core to the contaminant/air mass ratio and engine fuel flow.



Assumption 2

In low concentrations, engine core damage and hence additional cost is proportional to accumulated mass of ingested contaminant

- For fuel mileage, we assume a linear decrease per kg of core-ingested contaminant.
- For lifetime reduction, we assume a fixed number of hours per kg of core-ingested contaminant.



Conclusion

Additional cost is a linear function of fuel flow, contaminant mass ratio and exposure time

Advantages

Simply linking contamination effects to available aircraft performance parameters makes the method extremely suitable to high-performance trajectory optimization algorithms, like FLIGHTKEYS 5D.

At the same time, a level of detail down to tracking individual engines can be achieved without much effort.

Vertical Example A320neo, 67t

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Distance Cost [€/NM] over Altitude and Mach

Cvashmax	1	mg/m3
altCloud	33000	ft
vgradient	10%	/1000ft

	Mach													Cvash
	0.7	0.71	0.72	0.73	0.74	0.75	0.76	0.77	0.78	0.79	0.8	0.81	0.82	mg/m3
39000					9.0	8.8	8.8	8.7	8.7	8.9	9.2			0.40
38000			10.0	9.9	9.8	9.7	9.6	9.6	9.6	9.7	10.1	10.9		0.50
37000	11.0	10.8	10.7	10.6	10.5	10.5	10.4	10.4	10.4	10.6	10.9	11.7		0.60
36000	11.6	11.5	11.4	11.4	11.3	11.3	11.3	11.2	11.3	11.4	11.7	12.4	13.1	0.70
35000	12.4	12.3	12.2	12.1	12.1	12.1	12.1	12.1	12.2	12.3	12.6	13.3	14.0	0.80
34000	13.1	13.0	13.0	12.9	12.9	12.9	13.0	13.0	13.1	13.2	13.5	14.2	14.9	0.90
33000	13.7	13.8	13.8	13.8	13.7	13.8	13.8	13.9	14.0	14.1	14.4	15.1	15.8	1.00
32000	12.6	12.6	12.7	12.7	12.8	12.8	12.8	12.8	12.9	13.1	13.3	13.9	14.5	0.90
31000	11.5	11.6	11.6	11.7	11.8	11.9	12.0	11.9	11.9	12.1	12.3	12.8	13.4	0.80
30000	10.6	10.6	10.6	10.7	10.8	10.9	11.1	11.0	11.0	11.1	11.3	11.8	12.3	0.70
29000	9.8	9.8	9.8	9.8	9.9	10.0	10.2	10.1	10.1	10.2	10.4	10.8	11.3	0.60
28000	8.9	8.9	9.0	9.0	9.0	9.1	9.3	9.3	9.3	9.3	9.5	9.9	10.3	0.50
27000	8.1	8.2	8.2	8.2	8.2	8.3	8.4	8.5	8.5	8.5	8.6	9.0	9.3	0.40
26000	7.3	7.3	7.4	7.4	7.4	7.5	7.6	7.6	7.7	7.7	7.8	8.1	8.4	0.30
25000	6.5	6.6	6.6	6.6	6.7	6.7	6.8	6.8	6.9	6.9	7.0	7.2	7.5	0.20

Vertical Example A380, 350t

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Distance Cost [€/NM] over Altitude and Mach

Cvashmax	1	mg/m3
altCloud	33000	ft
vgradient	10%	/1000ft

	Mach														Cvash
	0.7	0.72	0.74	0.76	0.78	0.8	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88	mg/m3
41000		31.4	30.6	29.8	29.2	28.8	28.7	28.7	28.7	28.7	29.0	29.4	30.4	32.3	0.20
40000	38.0	37.0	36.0	35.2	34.7	34.4	34.4	34.3	34.4	34.6	34.9	35.4	36.5	38.4	0.30
39000	49.6	48.2	47.1	46.4	45.9	45.7	45.7	45.7	45.9	46.2	46.7	47.5	48.7	51.2	0.40
38000	54.5	53.2	52.3	51.8	51.4	51.3	51.4	51.5	51.7	52.1	52.8	53.8	55.3	58.1	0.50
37000	59.0	57.9	57.2	56.7	56.5	56.6	56.8	57.0	57.3	57.8	58.6	59.9	61.7	64.8	0.60
36000	63.3	62.4	61.8	61.5	61.5	61.8	62.0	62.3	62.7	63.3	64.2	66.0	68.1	71.5	0.70
35000	67.8	67.1	66.7	66.6	66.7	67.2	67.6	68.0	68.4	69.2	70.3	72.4	75.2	78.8	0.80
34000	72.3	71.7	71.5	71.6	71.9	72.5	73.0	73.6	74.2	75.1	76.5	79.0	82.3	86.2	0.90
33000	76.6	76.3	76.3	76.5	77.0	78.0	78.6	79.3	80.0	81.1	82.6	85.5	89.5	93.7	1.00
32000	69.8	69.7	69.9	70.2	70.9	71.9	72.6	73.3	74.0	75.0	76.4	79.4	83.3	87.5	0.90
31000	63.5	63.6	63.9	64.4	65.1	66.2	66.8	67.5	68.2	69.2	70.5	73.4	77.3	81.3	0.80
30000	57.5	57.8	58.2	58.8	59.6	60.7	61.3	62.0	62.6	63.5	64.8	67.6	71.3	75.1	0.70
29000	52.0	52.4	52.9	53.5	54.3	55.3	55.9	56.6	57.2	58.0	59.2	61.9			0.60
28000	46.7	47.2	47.7	48.4	49.2	50.2	50.7	51.3	51.9	52.7	53.8				0.50
27000	41.7	42.3	42.8	43.5	44.2	45.1	45.6	46.1	46.7						0.40
26000	36.9	37.5	38.1	38.7	39.4	40.2	40.7	41.1							0.30
25000	32.4	32.9	33.4	34.0	34.6	35.4									0.20

Applications

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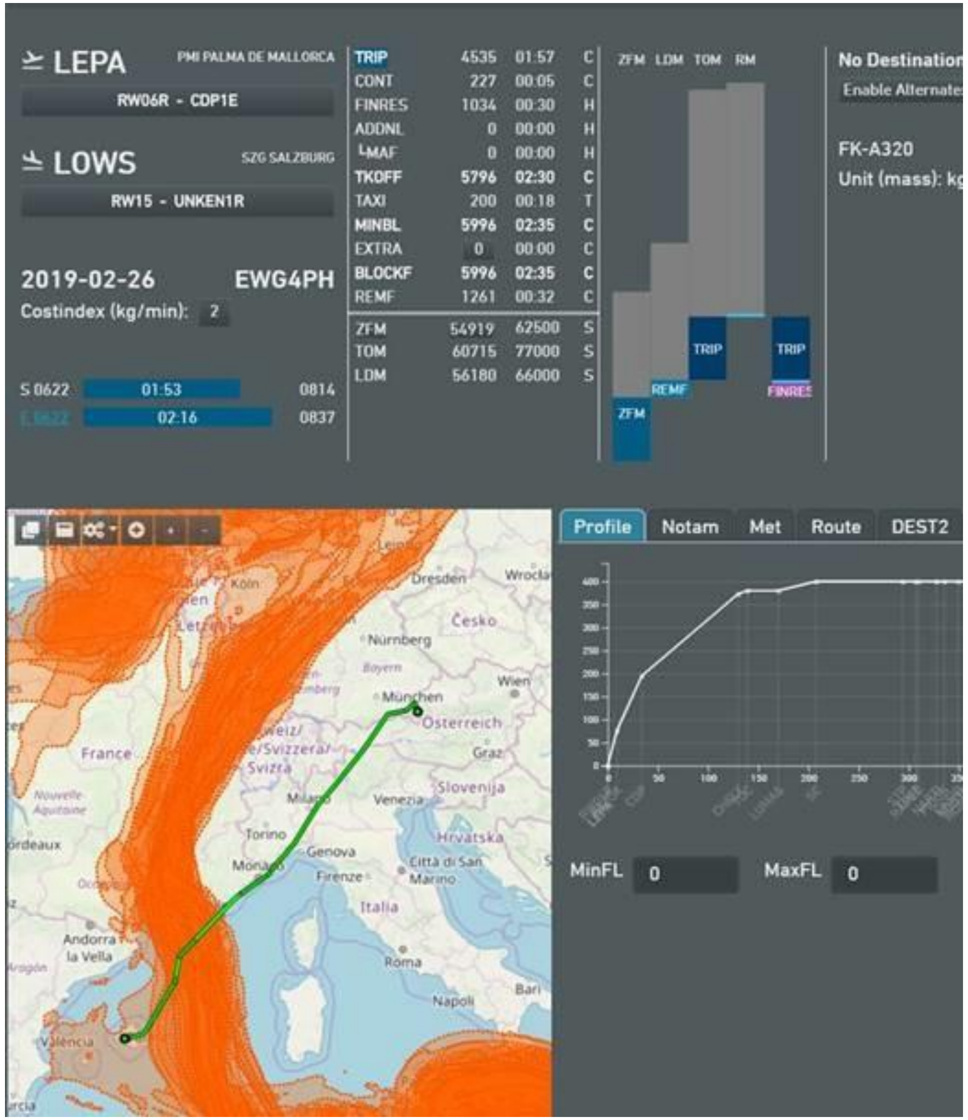
- Precise monitoring of total contamination exposure
- Prediction of engine lifetime impacts
- Bonus system for maintenance contracts
- Decision support in high-concentration events (volcanic activity, dust storms)
- Standardization of risk-assessment programs
- Full integration with cost-based trajectory optimization
- Automatic, cost-based avoidance of high-concentration events (volcanic activity, dust storms)

Win-win situation:

- Engine providers save on improved engine lifetime
- Aircraft operators save on fuel consumption and maintenance bonuses

Current Status

- Cooperation with Rolls-Royce on cost impact of aerosols in engine operations
- Basic algorithms and KPIs developed by FLIGHTKEYS
- Initial integration of algorithm into FLIGHTKEYS trajectory generator
- Import of 4D ash cloud simulation data into FLIGHTKEYS trajectory generator
- Large-scale simulation of European traffic in EUNADICS-AV exercise March 2019: 98000 flights re-optimized in ash scenario showing significantly reduced impact in cases of major volcanic eruptions (https://nhess.copernicus.org/articles/20/1719/2020/)



Tactical avoidance with EFB tools

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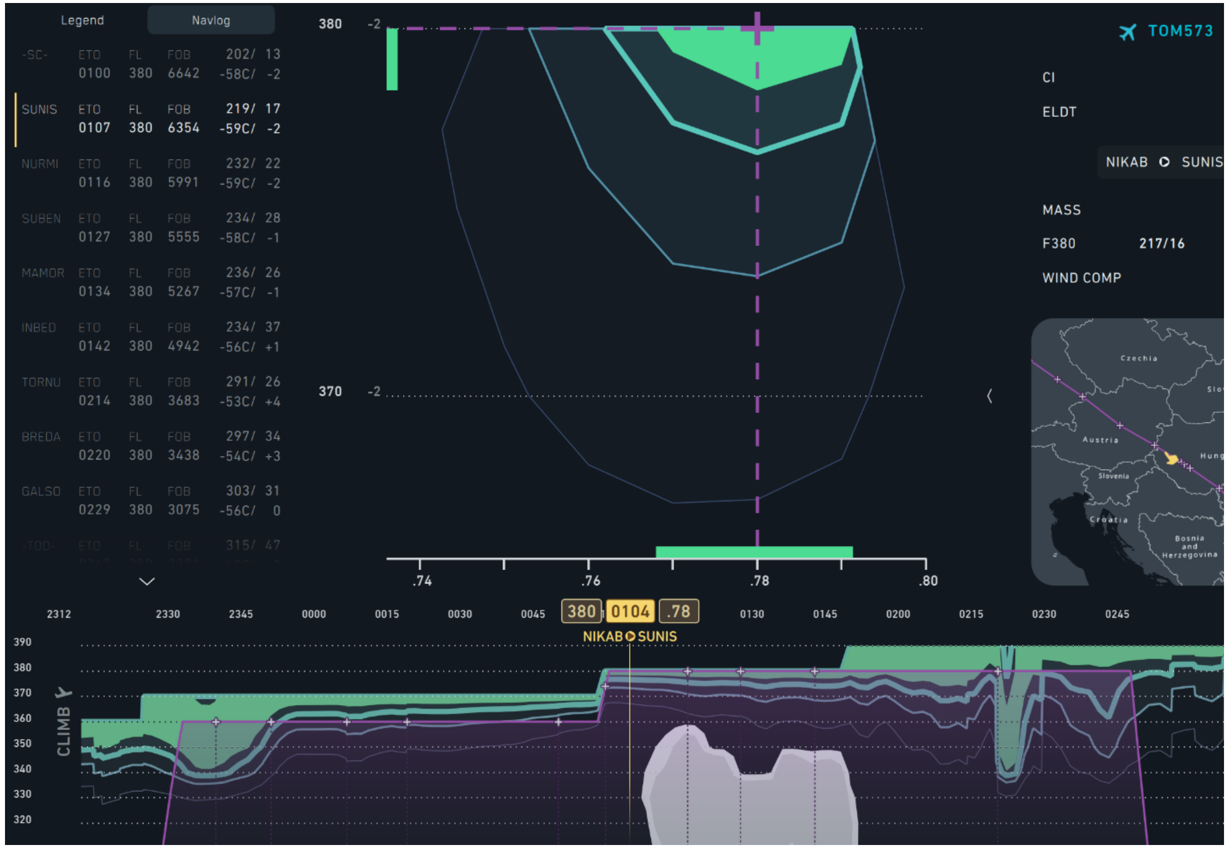
- Integration into EFB/FPO systems like Skykeys Loretta
- Using same cost-based algorithms as in flight planning
- Nowcasting possible with satellite connectivity
- Visualisation of vertical ash distribution



Next Steps

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- Validate assumptions with engine and aircraft manufacturers (ongoing cooperation with Rolls-Royce)
- Calibrate engine damage parmaters by recalculating flights from QAR data with contamination data and FLIGHTKEYS Zeta function
- Develop key parameters for most common engines (e.g. core contamination/damage ratios)
- Cost-Benefit analysis based upon large-scale simulations
- Full integration of contaminant concentration forecasts into FLIGHTKEYS trajectory generator
- Integration into EFB/FPO systems like Skykeys Loretta

Contact us:

Raimund Zopp
Director Innovation, FLIGHTKEYS
raimund@flightkeys.com

Photo: Peter Radler