ANALYSIS OF ATV DESTRUCTIVE RE-ENTRY INCLUDING EXPLOSION EVENTS

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ABSTRACT/RESUME

The ATV (Automated Transfer Vehicle) is a supply spacecraft for the International Space Station, ISS. After its nominal mission, docked to the ISS, it shall dispose waste of the space station and itself during a controlled re-entry into the atmosphere. The re-entry shall be conducted over non inhabited area with a possible ground risk below the accepted limits. While it is known that the ATV will burn up to a large extent, it has not been investigated yet, whether the tanks onboard the ATV may explode during re-entry, and whether this may increase or decrease the ground risk.
The ATV re-entry without explosions was studied some years ago with the SCARAB [1] software. To be able to treat the re-entry problem including explosions, the software has been extended and supplemented by additional tools. The extension covers the assessment of explosion likelihood by monitoring all events during re-entry, which contribute to an explosion environment and to explosion initiation. The supporting tools are an explosion model, based on the one used in NASA's EVOLVE 4 [2], and a fast object re-entry analysis tool, which allows the tracking of all fragments, generated by an explosion, till demise or ground impact.
This paper will outline these developments in detail and analysis results will be presented.

1. ASSESSMENT OF EXPLOSION LIKELIHOOD

In order to quantitatively assess the likelihood of an explosion the following subjects need to be considered:

- Explosion environment
- Matter initiating explosion and explosive limits
- Explosion matter release

The ~~Explosion environment~~ is the flow field surrounding the vehicle during the hypersonic re-entry phase. The hypersonic re-entry phase is characterised by:
• High flow velocity
• Low ambient pressure
• High temperature flow field around the vehicle containing atomic oxygen
• High wall temperatures up to material melting level

~~Explosive matters~~ are the ATV-specific hypergolic self-igniting propellants. These are MMH and MON-3 in the propulsion and re-boost system, and UDMH and NTO in the refuelling kits.

~~Explosive limits of released fuels~~
The explosive limit regimes are given in a pressure-temperature diagram with $p > p_{expl}(T)$. The explosive limit relations $p_{expl}(T)$ have been provided by Schmehl [3] for the following reactions:

- Auto-ignition of MMH/N2O4 mixture
- Auto-ignition of UDMH/N2O4 mixture
- Auto-ignition of MMH with O2 and atomic O

Fig. 1 shows these limits and the mean auto-ignition regime given by T>400K and p>250 Pa.

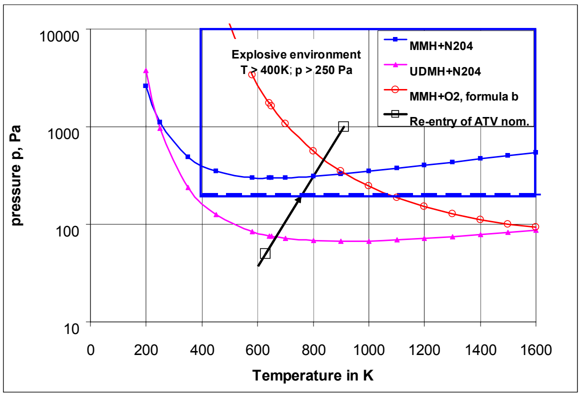

Figure 1: Auto-ignition limits of MMH/NO2, UDMH/NO2, MMH/O2 and intersection with ATV re-entry.

In order to asses the likelihood of an explosion we consider the following effects:
A. Effects, which produce an explosion environment
B. Effects, which could initiate an explosion

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A. Effects, which produce an explosion environment

- Ambient pressure: $P > P_{critical}$
- Ambient temperature $T > T_{critical}$

Environment factors for pressure E_P and temperature E_T are used.
$E_P = 0$ for $P < P_{critical}$; $E_P = 1$ for $P > P_{critical}$
$E_T = 0$ for $T < T_{critical}$; $E_T = 1$ for $T > P_{critical}$
The explosion environment is established for $E{:=}E_P E_T{=}1$.

B. Effects, which could initiate an explosion

- Fuel leaks
- Burst of fuel or oxidizer tanks
- Destruction of fuel or oxidizer tanks by fragments of bursting gas or water tanks
- Destruction of fuel or oxidizer tanks by fragment impacts

For quantification of events a status factor and influence factor of each event are introduced. The status factor S_i (0, 1) describes the occurrence of event i. The influence factor L_i (0-1) describes the event influence on an explosion. All contributors to A and B have been quantified as shown in Table 1.

Table 1: Explosion-related events, criteria and factors

I	Environment	Criteria	E_P; E_T
1	Pressure	$P_{dyn} > 250$ Pa	**0/1**
2	Temperature	$T_{wall} > 400$ K	**0/1**

II	Contributor to initiate explosion	Event criteria	Status S_i	Infl. factor L_i
1	Leakage of fuel	$T_{Valve} > 600$ K	0/1	0.4
2	Leakage of oxidizer	$T_{Valve} >$ 600K	0/1	0.2
3	Burst of fuel tank	$P_{Tank} > P_{Burst}$	0/1	0.9
4	Burst of oxidiser tank	$P_{Tank} > p_{Burst}$	0/1	0.5
5	Burst of gas or water tank	$P_{Tank} > P_{Burst}$	0/1	0.1
6	Tank destruction by fragments	Each fragmentation event	0/1	0.1

The evolution of the environment and the events during ATV re-entry can be monitored with SCARAB as shown in Figure 2.

Two probability functions are introduced: The complementary probabilities of no explosion and explosion. At beginning of re-entry the probability index of no explosion is set to $P_{No\ Expl.} = 1$ and the Probability for an explosion is equal to $P_{Expl} = 1 - P_{No\ Expl} = 0$.

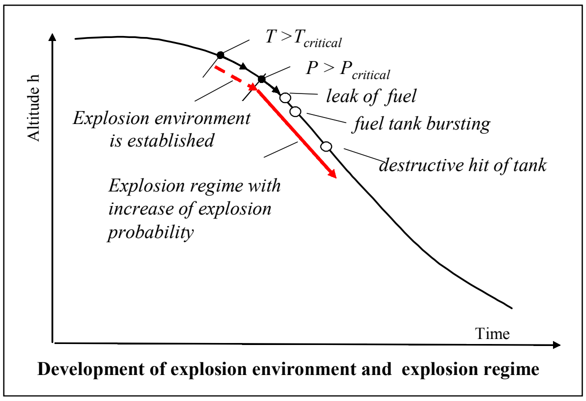


Figure 2: Development of explosion environment and explosion regime

Each event contributing to an explosion reduces the propability of no explosion by $1 - S_i L_i$. After applying the method of iterated products we obtain for the probability index for no explosion and for explosion the following expressions

$$P_{NoExplosion} = E \prod_i (1 - S_i L_i)$$
$$P_{Explosion} = 1 - E \prod_i (1 - S_i L_i)$$

A fuel tank bursting with L_i=0.9 produces as example an explosion probability index of $P_{Expl} = 0.66$ and 2 successive fuel tank bursts give an explosive index of $P_{Expl} = 0.85$. The limiting maximum value is $P_{Expl} = 1$.

2. SCARAB MODEL OF ATV WITH CARGO AND ERGOL LOADING

The ATV was originally modelled in 2001 for a re-entry analysis covering a nominal and a non-nominal configuration, covering the cases of successful and unsuccessful docking to the ISS. This modelling was based on ATV-PDR documents. An updating of the modelling was required, since the ATV final design, based on CDR documents, had to be considered, the dry cargo and fuel loading has been changed, and the modelling of tanks and tank content has been changed in SCARAB.

2.1 SCARAB Model of Dry ATV

Fig. 3 shows the complete ATV as modelled in SCARAB. The complete ATV SCARAB model consists of 294 basic geometric elements with 91544 surface panels. Fig. 4 shows views of the Equipped Propulsion Bay and the Equipped External Bay. Fig. 5 shows a cut up view into the equipped pressurized module EPM.

Mass, center of mass, and moments of inertia of the dry ATV are compared in Table 2.

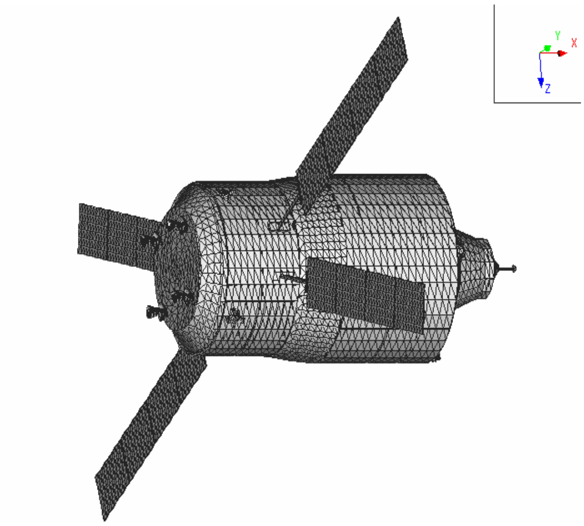


Figure 3: View of the ATV SCARAB model

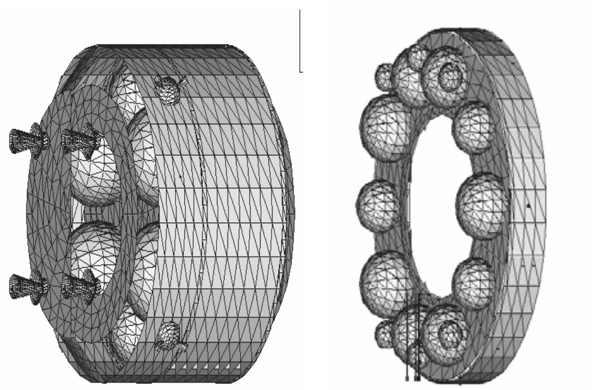


Figure 4: The Equipped Propulsion Bay, EPB, and the Equipped External Bay, EEB.

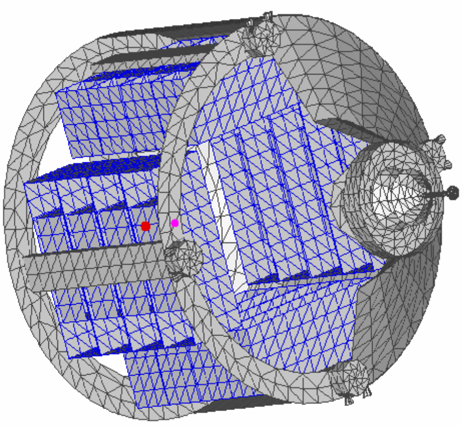


Figure 5: View into cut-up Pressurized Module, EPM.

Table 2: Mass properties of the modelled ATV

	Mass kg	**$X_{C.M}$ m**	**$Y_{C.M.}$ M**	**$Z_{C.M.}$ m**	**Ixx Kgm^2**	**Iyy kgm^2**	**Izz kgm^2**
ATV	10362	3.654	-0.0095	-0.053	35378	71013	77192
Model	10368	3.618	0.0004	-0.027	36830	69880	73730

2.2 The Modelled Cargo and Fuel Loading

For the tank bursting analysis of SCARAB information about the contents of each tank is required. ATV carries in total 26 tanks. Due to interconnections between tanks in the EPB the effective total number of tanks is reduced to 22. Table 3 shows a summary of cargo and fuel loading, Table 4 shows detailled information about all tanks.

Table 3: Cargo and fuel loading of the ATV model

ATV/Cargo/location	**Type**	**Mass, kg**
ATV dry, free flight	Divers	**10367.8**
Dry Cargo/EPM	Divers	5500.0
Prop-Ergols/EPB	MMH	946.1
	MON	1583.7
	He	28.4
	Total	**2558.2**
Refuel Ergols/EEB	UDMH	4.0
	NTO	8.0
	He	3.3
	Total	**15.3**
Gas/EEB	N2	0.2
	O2	0.3
Water/EEB	Liquid H20	840.0
Total		**19281.8**

Table 4: Properties and contents of all tanks

	Tank	No	Vol. m^3	Pb, bar	Liquid	Mass Kg	Gas	Mass kg
Propel.	PT1,PT6	**1**	1,68	45	MMH	473,1	He	3,360
EPB	PT2,PT5	**2**	1,68	45	MON	791,8	He	3,340
	PT3,PT8	**3**	1,68	45	MMH	473,1	He	3,360
	PT4,PT7	**4**	1,68	45	MON	791,8	He	3,340
	PG-T1	**5**	0,4	820			He	7,500
	PG-T2	**6**	0,4	820			He	7,500
R.efuel	RFS-F	**7**	0,215	45	UDMH	2,0	He	0,663
EEB	RFS-O	**8**	0,215	45	NTO	4,0	He	0,662
	RFS-P	**9**	0,02	800			He	0,110
	RFS-P	**10**	0,02	800			He	0,110
	RFS-P	**11**	0,02	800			He	0,110
	RFS-F	**12**	0,215	45	UDMH	2,0	He	0,663
	RFS-O	**13**	0,215	45	NTO	4,0	He	0,662
	RFS-P	**14**	0,02	800			He	0,110
	RFS-P	**15**	0,02	800			He	0,110
	RFS-P	**16**	0,02	800			He	0,110
Gas	GTA	**17**	0,13	560			N2	0,150
EEB	GTA	**18**	0,13	560			O2	0,150
	GTA	**19**	0,13	560			O2	0,150
Water	WTA	**20**	0,301	8	H2O	280,0	N2	0,024
EEB	WTA	**21**	0,301	8	H2O	280,0	N2	0,024
	WTA	**22**	0,301	8	H2O	280,0	N2	0,024
	Total					**3381,8**		**32,23**

3. EXPLOSION MODEL AND EXPLOSION CLOUD ANALYSIS

The analysis of an explosion during re-entry and its effect on ground risk due to surviving fragments comprises the following three tasks:

- Re-entry analysis of the intact spacecraft until an explosion event is detected, which is covered by SCARAB
- Explosion fragment generation based on the spacecraft state at the time of explosion
- Re-entry analysis of the fragments

3.1 The Explosion Model

In order to determine the destruction of a spacecraft due to an explosion a mathematical model is needed which describes the number of generated fragments and their mass, size, shape, and velocity characteristics. After a critical review the NASA EVOLVE 4 breakup model has been selected. This model is based on observed fragment clouds of orbital break-ups. It is also used in the current MASTER 2001 debris flux modelling software.

The number of explosive fragments (N) of size L_c or larger is given in this model by: $N(L_C) = 6S \times L_C^{-1.6}$
where S is a simple scaling factor for for mass conservation. The break-up model uses statistical distribution functions for the fragment data with a general distinction between spacecraft and upper stage explosions.

The statistical *A/M* distribution for objects with L_c larger than 11 cm is a bimodal normal distribution function:

$$D_{A/M}(\lambda_c,\chi) = \alpha(\lambda_c) N\left(\mu_1(\lambda_c),\sigma_1(\lambda_c),\chi\right) + \left(1-\alpha(\lambda_c)\right) N\left(\mu_2(\lambda_c),\sigma_2(\lambda_c),\chi\right)$$

with $\lambda_C = \log_{10}(L_C)$, $\chi = \log_{10}(\mathrm{A/M})$.

$N(\mu,\sigma,\chi)$ is the standard normal distribution function.

The average cross-section A_x is modeled as an exponential function of L_c:

$A_x = 0.556945 L_c^{2.0047077}$ for $L_c > 0.00167$ m

The mass of the fragments can be simply obtained by:
$M = A_x/(A/M)$.

The fragment ejection velocity distribution is modeled as a standard normal distribution function.

$$D_{\Delta V}(\chi,\nu) = N\left(\mu(\chi),\sigma(\chi),\nu\right)$$

with $\nu = \log_{10}(\Delta \mathrm{V})$.

The peak of this function is shifted to larger ΔV values for larger A/M ratios (i.e. smaller masses), thus lighter fragments get higher ejection velocities.

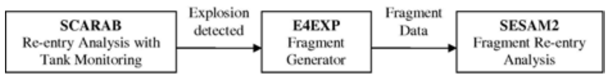
3.2 The Explosion Model E4EXP Implementation

The fragment generator E4EXP is a modified EVOLVE break-up model and serves as an interface between the two re-entry analysis tools SCARAB and SESAM2, a 3D trajectory propagator. The task of SESAM2 is to conduct a fast re-entry analysis for the fragments generated by the explosion. Basic requirements for E4EXP are:

- Mass conservation for each material
- Thermal energy conservation

The input data for SESAM2 for each fragment are:

- Geometric shape (sphere, cylinder, box, or flat plate) and dimensions
- Object mass and material
- Initial state vector (ATV state vector + ejection velocity vector) and temperature



The new explosion E4EXP model needed the following extensions of the EVOLVE model:

- Object shape identification from A/M, L_c, M
- Mass conservation for each material. This was solved by calculation for each material an individual explosion cloud.
- Thermal energy conservation during explosion

The application result of the explosion model to a rocket body consisting of 3000 kg Aluminum is shown in Fig. 6. 108505 boxes (92.2%), 7507 cylinders (6.4%), and 1445 spheres (1.2%) were identified. The shape of 209 fragments (0.2%) could not be identified.

In order to reduce the number of objects to be analyzed by SESAM2 the critical objects have been determined based on the maximum tolerable impact energy 51.5 J [4]. After filtering out the uncritical objects 1125 critical objects remained, consisting of 597 boxes, 322 cylinders and 206 spheres.

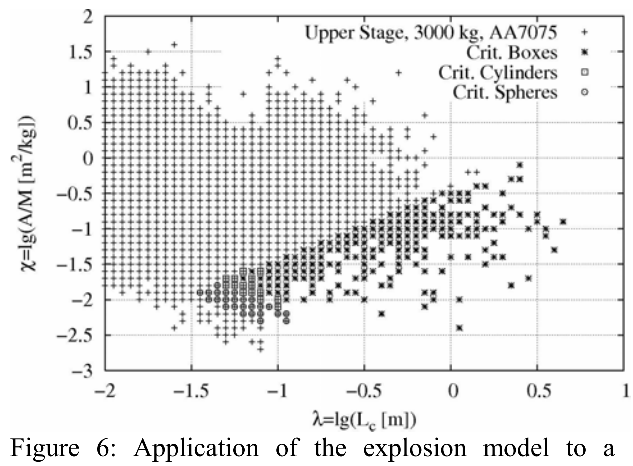


Figure 6: Application of the explosion model to a 3000kg upper stage. The critical objects are shown on the right lower side.

4. ATV RE-ENTRY ANALYSIS AND EXPLOSION INDEX

SCARAB is used to calculate the re-entry behaviour of ATV, starting at the re-entry interface at 120 km geodetic altitude. During trajectory propagation all possible contributions to the explosion environment are monitored. For the explosion index assessment the calculation proceeds until the end of the hypersonic flight regime, just recording the possible explosion events. The events to be monitored were shown in Table 1.

There are two environment conditions, 22 tanks and 10 valves to be checked. Fig. 8 shows as an example the temperature evolution of the fill and drain valves, which are responsible for leaks. There are 10 FDVs in total. A valve is assumed to fail (leak) when its temperature exceeds 600 K. Figure 8 shows the distribution of all detected explosion-related events along the ATV re-entry trajectory.

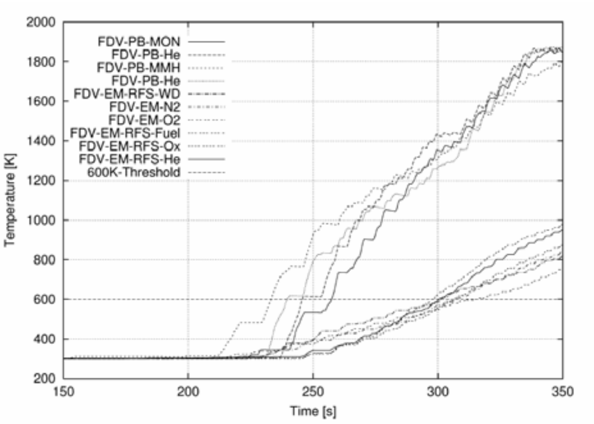


Figure 7: Temperature evolution of feed and drain valves during re-entry.

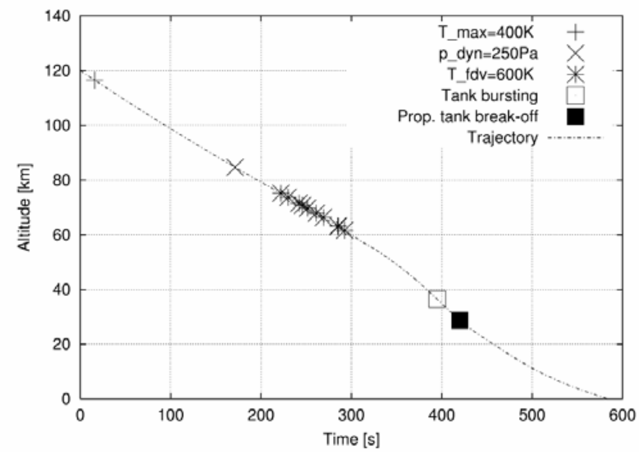


Figure 8: Detected explosion-related events during re-entry.

Figure 9 shows the explosion probability index computed from the explosion event distribution and the status/influence factors defined in Table 1. For example, an explosion index of 71 % is reached after 285.5 seconds at an altitude of 63.11 km, after the 9th explosion related event, which was a leakage of valve no. 8.

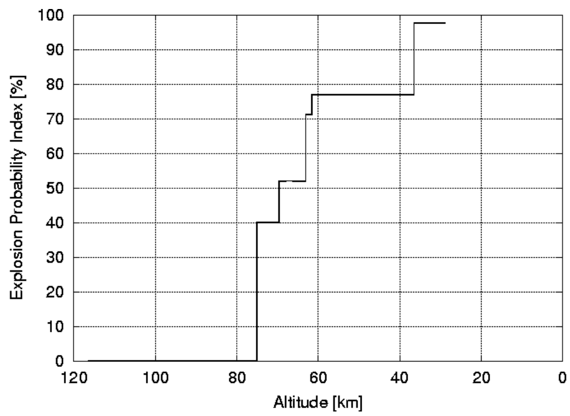


Figure 9: Evolution of Explosion Probability Index during re-entry.

5. INFLUENCE OF EXPLOSIONS ON GROUND IMPACT

5.1 Explosion Fragments and Survival Analysis

The analysis of an explosion was performed assuming an explosion altitude of 75 km. The material-specific mass and thermal budget at this altitude was supplied by SCARAB. The fragment generator E4EXP was used to generate the fragment clouds for each material, and SESAM2 was used to assess the fragment survivabilty. Table 5 summarises the results.

Table 5: Result of the survival analysis for the different material clouds

Material	Initial Fragments	Surviving Fragments	Surviving Fraction [%]
AA7075	3578	3	0.1
HC-AA7075	141	1	0.7
TiAl6V4	344	94	27.3
A286	466	74	15.9
CFRP	115	115	100
Copper	362	4	1.1
Niob-C103	64	25	39.1
Inconel718	104	3	2.9
AA2219	953	2	0.2
A316	118	37	31.4
AA6060-63	229	0	0
Total	**6474**	**358**	**5.5**

In the 11 fragment clouds for the different ATV materials an initial number of 6474 fragments are generated. From these fragments a total number of 358 (5.5%) survives the re-entry. From the initial exploding ATV mass

of 15520 kg only 12.5 % reaches ground. Materials with high melting temperature have a higher probability to survive than materials with low melting temperatures.
The resulting ground track of the survival fragments is shown in the next figure. The groundtrack of the explosion fragments covers a longitude span of 9 deg.

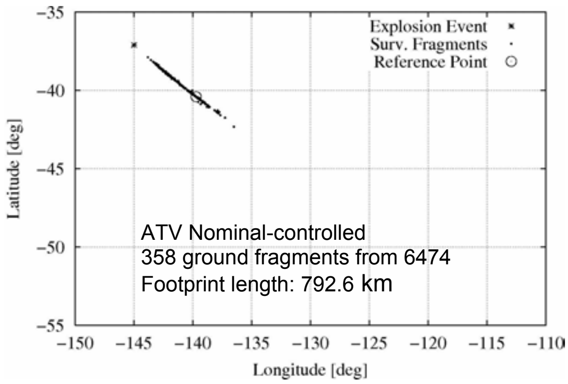


Figure 10: Ground impact foot print of an ATV explosion cloud generated at 75 km altitude.

5.2 Re-entry/Survival Analysis without Explosion

For comparison we have analysed the ATV destructive re-entry without considering an explosion. Fig. 11 shows the trajectory of the main fragment, which is the surviving fragment with the largest mass, with indication of all its fragmentation (break-off) events.
Above 75 km altitude, at which an explosion was analysed, only one main fragmentation event occurred (loss of solar arrays). Main fragmentation started at 65 km altitude and continued down to 30 km.

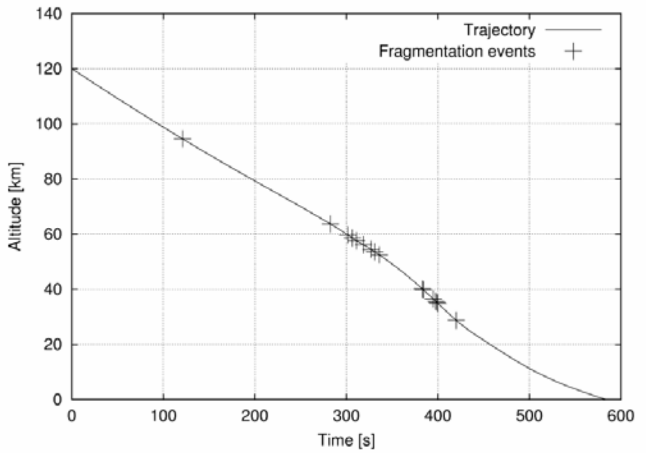


Figure 11: Trajectory and fragmentation events for the main fragment during nominal controlled ATV reentry

The ground impact footprint of ATV fragments without explosion is shown in Fig. 12. The main ATV fragment has the longest downrange. Only one fragment is generated before the explosion altitude of 75 km. From fragments generated by SCARAB after the virtual explosion altitude, 21 reach the ground. The ground track covers a longitude span of 4 deg.

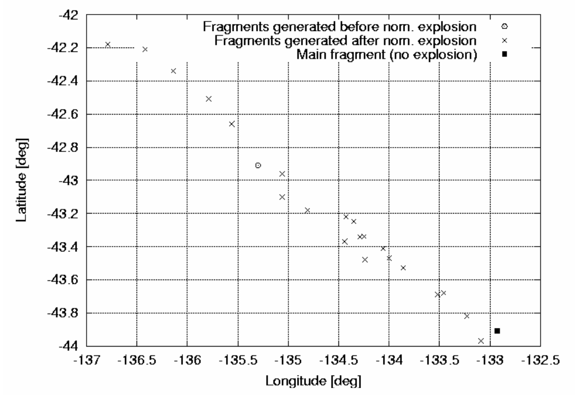


Figure 12: Surviving ground impact footprint of ATV fragments without explosion.

6. CONCLUSION

A method to quantify explosion likelihood along the reentry trajectory has been developed. The method uses status factors Si and influence factors Li. Status factors Si can directly be determined with SCARAB by control functions. Influence factors Li have to be set by the user and show the importance of an event for initiation of an explosion
A modified NASA EVOLVE break up model has been used to determine the explosion fragment cloud.
An explosion at 75 km altitude will destroy ATV into a cloud with 6474 fragments. From this fragment cloud only 5.5% will reach the ground.
High altitude explosions will strongly reduce the ground impact mass of ATV; however the ground impact footprint will be stretched.

7. REFERENCES

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