Determination of the Radiation Dose of the Apollo 11 Mission

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1 Motivation and Introduction

Every electronic unit which is used on a Space Craft has to be specifically robust so that it can be operated under the radiation environment in space. Often it is packed in a metallic housing so that the necessary radiation protection is achieved. As electronic units as men are susceptible to ionising radiation.
It would be interesting to know what radiation dose the Apollo astronauts have received. To this topic one can find an information in the NASA document „Space Faring - The Radiation Challenge“ [1]: For Apollo 11 there are 0.18 rad indicated.
In the Apollo 11 documentation there are several inconsistencies [17]. For this reason the radiation dose shall be checked according to the latest radiation models. In the same time the radiation risk of manned missions to the Moon and Mars is estimated.

2 Radiation Data

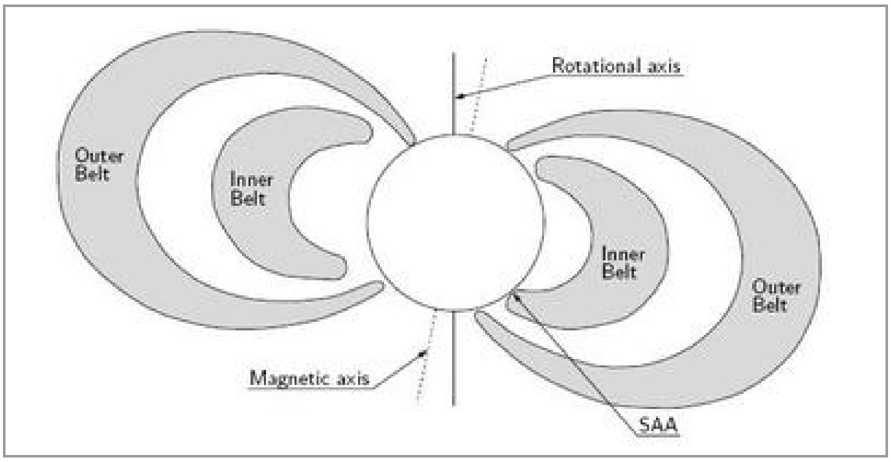
In the „Preliminary Science Report“ [2] on page 39 there are „Solar Corona Observations“ mentioned. This could be an indication to radiation. This was of interest because with a high probability solar flares could have been lethal to the astronauts. But there is no information about radiation.

The 0.18 rad from [1] correspond to 1.8 mGray or (optimistically) 1.8 mSv (Milli-Sievert). Sievert indicates the biological effect; but depending on the kind of radiation and tissue there is a weighting factor of > 1 to be considered for the conversion from Gray to Sievert. If Grays are 1:1 converted to Sievert then in general there results a too low dose value in Sievert.

As a comparison the annual terrestric dose level is according to [3] for the year 1999 4.5 mSv, other sources show 2.5-4.5 mSv/year. This means, the 1.8 mSv are a small additional exposure.
Another example were an astronaut in a space craft orbiting the earth 1'000 km above the equator. If the space craft were well protected with 4 mm Aluminium shielding then he would be exposed to a dose rate of 2.7 mSv/h [4]. This would be about one natural annual dose per hour.

The explanation for this high level is the Van Allen Radiation Belt which encircles the Earth: from a few hundred kilometres altitude the radiation rapidly grows. At 1'000 km above the equator it is – as shown before – quite high and further increases. At 3'000 km above the equator the dose rate is 465 mSv/h (always with 4 mm Aluminium shielding), and only after 40'000 km the dose rate falls below the value of 1'000 km altitude.

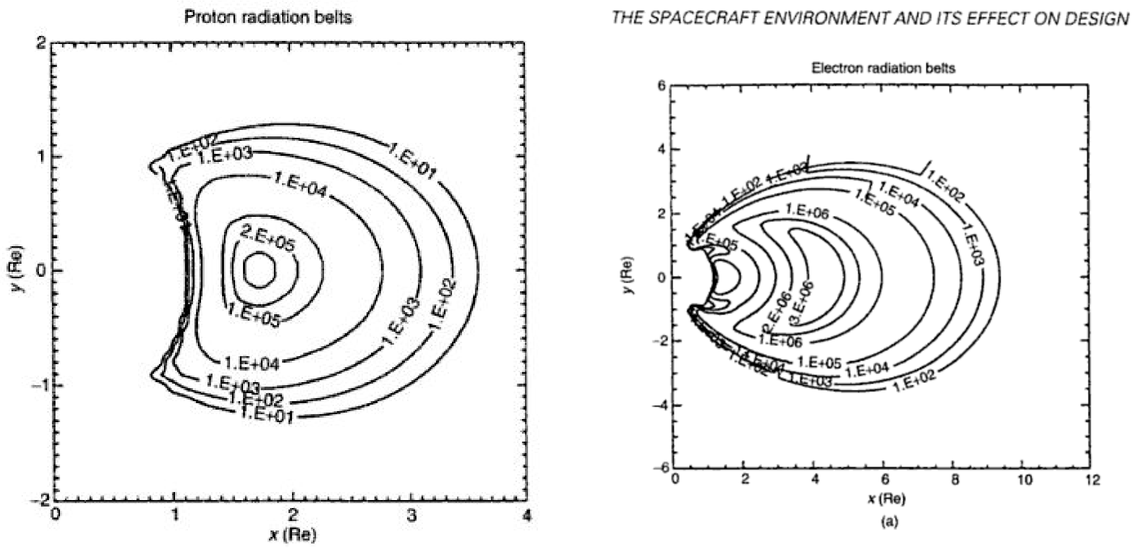
To fly to the Moon and back one does not have to cross the Van Allen Radiation Belt through its centre, but generally in a way so that one is longer than one hour within this belt.



Earth radiation belts with the South Atlantic Anomaly indicated

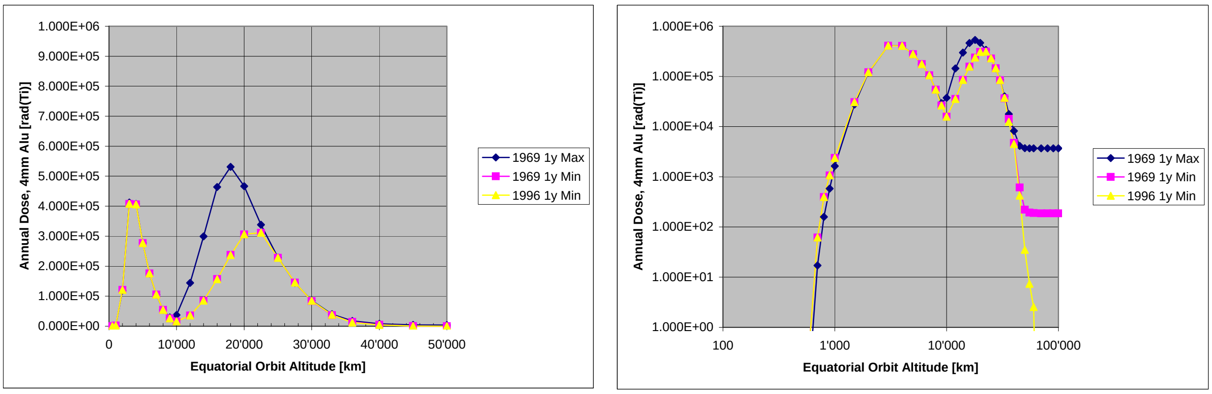
Figure 1 Van Allen Radiation Belt according to [7]

The following two figures show the situation in the Van Allen Radiation Belt more in detail: first a diagram with level curves, which indicate the number of high energy particles, then the total annual dose as a function of the altitude above the equator:



Re means Radius of the Earth (6370km); from [5]

Figure 2 Number of high Energy Protons (left) and Electrons (right)



The scaling on the left is linear, on the right logarithmic. The data is identical.

Figure 3 Annual Dose in the Van Allen Radiation Belt; determined with [4]

The diagram on the right corresponds well with similar diagrams in [5] and [18]. In Figure 3 the dose level is shown for tissue (Ti), on the comparative diagrams it is shown for silicon (Si). For tissue the dose level is about 30% higher. But this is hardly visible on the logarithmic scale.

The dose levels of Figure 3 refer to equatorial orbits. The equatorial plane is inclined with respect to the symmetry plane of the Van Allen Radiation Belt (i.e. the plane perpendicular to the magnetic axis, see Figure 1 or Figure 4), so that equatorial orbits are not always in the area of the maximum radiation. This means that in the centre of the Van Allen Radiation Belt there are even higher dose rates than shown in the above figure.

With the annual doses one can determine the total dose of a mission only then exactly if the radiation over the year is constant. In the Van Allen Radiation Belt there is a constant (base) radiation of the free electrons and protons which are always there. Additionally there is a variable part of proton radiation from the Sun. Further radiation is neglected here.

On the Moon the ionising radiation depends mainly on the activity of the Sun. If the Sun is not active the radiation is almost zero. At an eruption or flare, according to [14] there can occur up to 10 Sv per event, what „in fact should be deadly“.

Since the radiation beyond the Van Allen Radiation Belt (VAB) up to the Moon remains constant, an astronaut flying to the Moon is exposed to this radiation over a long time. Averaged over the year 1969 the total radiation dose beyond the Van Allen Radiation Belt was significant, as the following table shows[1].

[1] Determined from the Solar parts of Figure 3 right, „1969 1y Max and Min“. At 4mm Alu shielding the upper part adds up to about 3700 rad/y, which corresponds to ≥37 Sv/y or ≥4.2 mSv/h, the lower part adds up to about 190 rad/y or ≥1.9 Sv/y or ≥0.2 mSv/h.

Shielding [mm Aluminium]	High particle fluences from the Sun („Max“ or confidence level=95%)		Low particle fluences from the Sun („Min“ or confidence level=50%)	
	Dose over 2h (on the Moon) [mSv]	(Travel) Dose over 180h (7.5d) [mSv]	Dose over 2h (on the Moon) [mSv]	(Travel) Dose over 180h (7.5d) [mSv]
0.05	810.18	72'854.2	217.57	19'564.7
0.1	415.70	37'392.2	77.80	6'995.9
0.2	215.86	19'410.7	30.07	2'704.3
0.3	150.10	13'496.9	18.21	1'638.0
0.4	113.83	10'236.1	12.51	1'125.3
0.5	90.46	8'135.5	9.16	823.6
0.6	74.29	6'681.7	7.00	629.0
0.8	54.64	4'913.8	4.63	416.4
1	43.24	3'889.1	3.41	306.4
1.5	27.93	2'509.2	1.92	172.8
2	20.14	1'810.9	1.27	114.3
2.5	15.42	1'386.9	0.91	81.7
3	12.20	1'097.3	0.68	60.8
4	8.43	757.7	0.43	38.3
5	6.24	561.6	0.30	26.5
6	4.96	446.2	0.22	20.0
7	4.01	360.8	0.17	15.5
8	3.34	300.4	0.14	12.5
9	2.86	257.5	0.12	10.4
10	2.45	220.7	0.10	8.7
12	1.91	171.5	0.07	6.5
14	1.51	135.5	0.05	4.9
16	1.23	110.6	0.04	3.9
18	1.03	92.9	0.04	3.2
20	0.87	77.9	0.03	2.6

Table 1 Dose outside the VAB, Average for 1969, determined with [4]

The values from Table 1 exceed the reported information from the Apollo 11 mission (1.8 mGy) by far – even for a high shielding. They show the serious risk, i.e. what could happen if the Sun were active as usual. By the way, even today a solar eruption can not be predicted, not even one day in advance.

But these average values yield for short missions wrong values. According to spenvis [4] the radiation dose from the Sun originated in the year 1969 mainly from a short active phase: *„Cycle 20 had one anomalously large event that accounted for most of the accumulated fluence.“* [Cycle 20: 1966-1972]

Because of the unique event in the solar cycle of 1966-1972 one could assume that during the Apollo 11 mission only little or even no (proton) radiation was irradiated from the Sun. For this reason in the following a totally radiation-inactive Sun is assumed and only the base radiation, which is always present, is considered, i.e. the yellow curve in Figure 3.

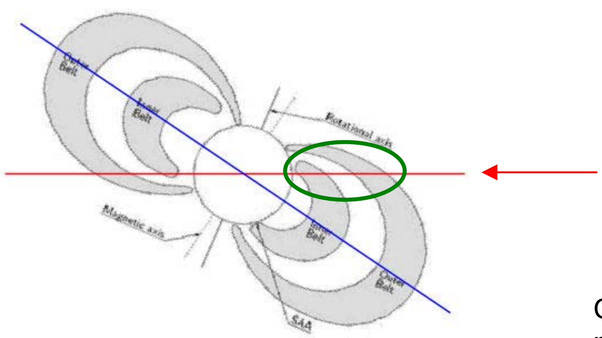
3 Estimation of the Radiation Dose according to a Theoretical Flight Path

To determine the radiation dose of the reported Apollo 11 mission, in case of doubt there is always taken the smallest value for the total dose. So at the end the result is a lower limit of the total dose. A reason for this is the official total dose value of 1.8 mGray which looks low. Here it shall therefore be investigated whether under favourable circumstances such a low level can be maintained.
The approach as follows:

1. The Van Allen Radiation Belt shall be crossed at its border. A maximum crossing angle of 35° shall be assumed (heuristic approach which will be refined in the next chapter):
   - The Earth axis is 23.5° inclined relative to the ecliptic (plane of the Earth orbit around the Sun)
   - The magnetic pole was in 1969 11.5° displaced relative to the geographical north pole ([11], see also Figure 1)

   ⇒ Therefore the Van Allen Radiation Belt can have had a maximum inclination of 35° with respect to the ecliptic.
2. In the radiation determination program [4] all switches have been set to „Minimum“ to achieve as small as possible total dose levels. In particular there has been assumed that there is <u>no contribution from the Sun</u> at all. „No contribution from the Sun“ can be correct for a certain period of time, in a year of a solar minimum this is the normal case. But for the year 1969 where there was a solar maximum [4] this assumption is optimistic, even when in that year the solar activity was smaller compared to earlier solar maximum years and when the main part of the total dose in that cycle came from one single event. Summarised only the part of the radiation in the Van Allen Radiation Belt is considered which is always present, i.e. the radiation of the „trapped“ free protons and electrons.
3. The total dose of Figure 3 is calculated for equatorial orbits, it therefore corresponds already to a mean value in a cone of ±35° (in Figure 5). In this calculation there results a too low total dose value for the centre of the Van Allen Radiation Belt. All the same this too low value shall be taken as the central value.
4. The radiation dose is calculated in Sievert. Gray is 1:1 converted to Sievert, i.e. there results a too low dose in Sievert. For the verification of the NASA value this has no impact, because the NASA value is given in rad (1 rad = 10mGray). The value in Sievert is only used for the biological effect.

Figure 4 shows the constellation of the magnetic axis where the Van Allen Radiation Belt is maximum inclined with respect to the ecliptic.

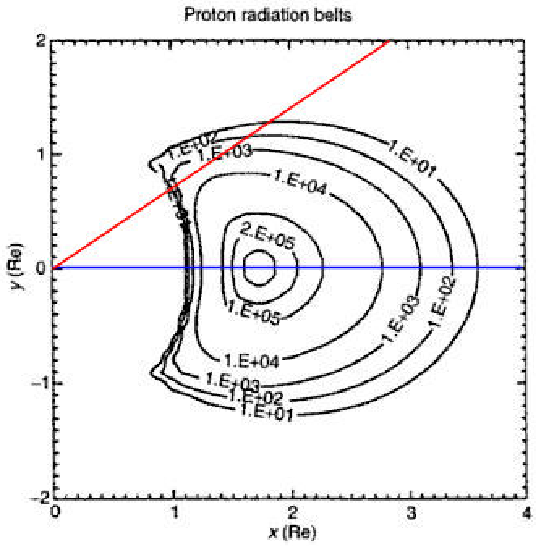


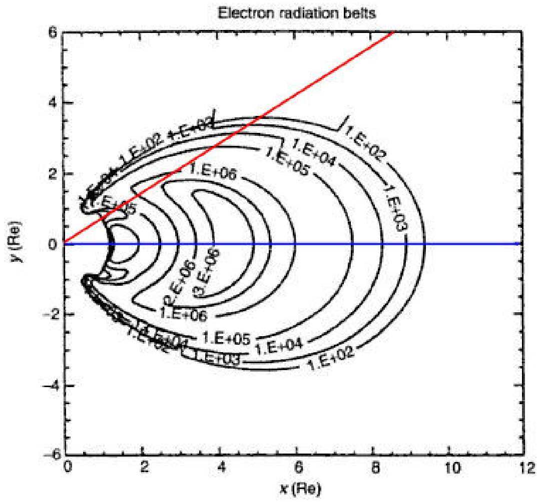
Ecliptic, 35° inclined w.r.t the Van Allen Radiation Belt

Green Ellipse: possible exit on the narrowest place

Figure 4 Van Allen Radiation Belt with maximum inclination to the ecliptic

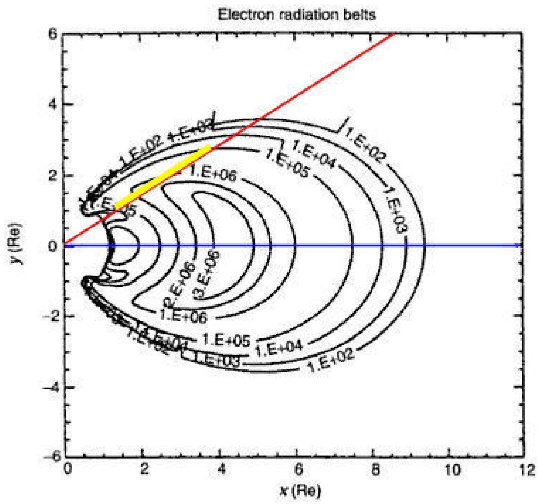
The lunar orbit is inclined another 5° with respect to the ecliptic, but the Moon was at the reported arrival of the Apollo 11 module quite exactly in the ecliptic [12]. These 5° may not be added in the case of Apollo 11. The constellation has anyway to be good so that all these angles can directly be added.
Apollo 11 could have left the Van Allen Radiation Belt in the best case under an angle of 35° to get a minimum radiation dose. The following figures show the situation for protons and electrons separately:





The red line has an angle of 35° w.r.t. the blue axis.
The 35° are composed as follows:
23.5°: Inclination of the Earth axis w.r.t the ecliptic
11.5°: Angle between the Earth dipole axis and the Earth (rotational) axis

The red line corresponds to the ecliptic at the maximum inclination w.r.t. the Van Allen Belt.



The path length in the zone with more than 1E+05 high energy electrons (yellow marked) is 3.1·Re ≈ 20'000km.
40% of it are in the zone with more than 1E+06 high energy electrons.

Figure 5 **Van Allen Radiation Belt and exit direction to the Moon with minimum radiation load**

Concerning the protons one could have flown quite a long distance away from the maximum. For the electron belt one would clearly have had to cross the zone with more than 1E+05 high energy electrons.

But Figure 5 shows that the exit path in the electron belt leads through an area where already small changes (e.g. upwards) have a large effect.
If therefore the described Apollo 11 flight path were located slightly above the shown line then the dose calculation along the red path would yield a too high dose. For this reason in the next chapter a total dose calculation is made with the flight path as it is described in the Mission Report.

4 Estimation of the Radiation Dose according to the Exact flight Path

The basic assumptions for the total dose calculation are unchanged with respect to the previous chapter. Also here a value shall be calculated which could have been achieved under the most favourable radiation conditions.
Here the exact flight path is used. It is described in §6.
The flight to the Moon and the flight back to the Earth are calculated separately.

The following two figures show the path through the radiation belt, the closer part with protons by the majority and the more distant part with electrons by the majority. On the top there is the path to the Moon, on the bottom the return to the Earth. The small red circles are points of the flight trajectory as they are given in the „Apollo 11 Mission Report“ [13].
Additionally in Figure 7 the associated manoeuvre is indicated. Surprisingly the rotation of the LM is in the area of the maximum radiation for the described path.
The small blue circles are points which have been used to transfer the trajectory into Figure 6 and Figure 7. These are often entry or exit points of radiation zones (see Table 2).

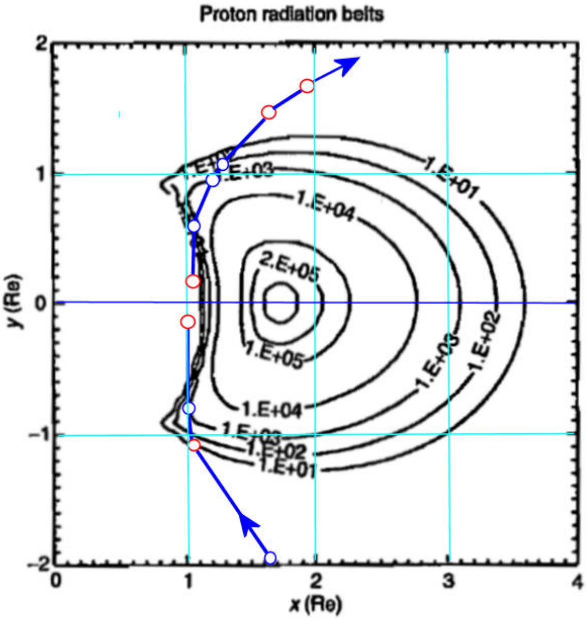


Figure 6 Flight Trajectory through the Proton Van Allen Radiation Belt

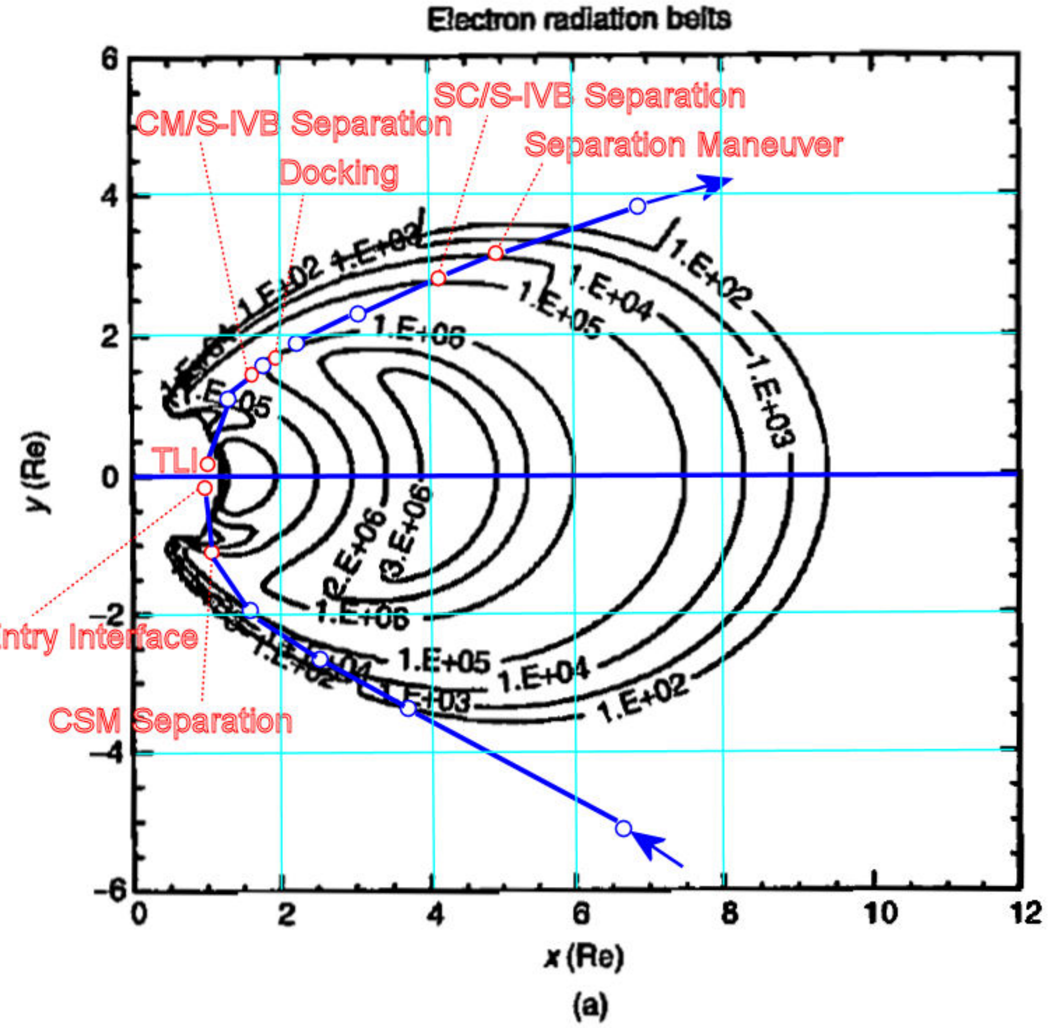


Figure 7 Flight Trajectory through the Electron Van Allen Radiation Belt

Comparing the above two figures with the ones in the previous chapter one recognises that the flight path obviously crosses the Van Allen Radiation Belt quite exactly at its maximum inclination. Additionally to the extreme exit angle the Apollo 11 trajectory to the Moon is slightly above the ecliptic so that there results a smaller dose compared to the previous chapter.
Also the return path is more favourable. Here the fact helps that the Moon was at the time of the reported departure from the Moon already 2° below the ecliptic.

With this data and the knowledge of the exact time between the different points of the trajectory the total radiation dose can be determined.
The total dose is calculated analogously to the level curves of the high energy protons and electrons, i.e. the maximum dose in the centre of the two belts is reduced according to the level curves. This procedure is justified on the one hand that the total dose is proportional to the number of the (high energy) particles, on the other hand in Figure 3 (annual dose) the total dose decreases along the x-axis in the same extent as the level curves in Figure 2, about a factor of 3 per Earth radius.

The calculation of the total dose is demonstrated for a shielding of 4 mm aluminium. The maximum intensities are according to Figure 3.
Table 2 shows the determination of the total radiation dose, where as described earlier only the permanent available radiation in the Van Allen Radiation Belt is counted.
For the proton belt a maximum intensity of $4.1 \cdot 10^5$rad/year or 465mSv/h is taken, for the electron belt $3.1 \cdot 10^5$rad/year or 355mSv/h.
For the intensity the low value of the respective zone is used. From the maximum of all zones ($3 \cdot 10^5$ or $3 \cdot 10^6$) to the next lower zone (the lower end is a power of 10) the maximum value is reduced by a factor of 3, then for every lower zone by another factor of 10.

	Zone	Time in Zone	Dose Calculation	Dose
Path to the Moon	1E4..1E5 e^-	≈0s	≈0 mSv	≈0 mSv
	1E5..1E6 e^-	800s ≈ 13min	800s* (1/30)*355mSv/h	>2.6 mSv
	>(≈)1E6 e^-	700s ≈ 12min	700s* (1/3)*355mSv/h	>(≈)23.0 mSv
	1E6 .. 1E5 e^-	2700s = 45min	2700s* (1/30)*355mSv/h	>8.9 mSv
	1E5..1E4 e^-	1383s ≈ 23min	1383s* (1/300)*355mSv/h	>0.5 mSv
	1E3 .. 1E4 p^+	400s ≈ 7min	400s* (1/300)*465mSv/h	>0.2 mSv
Total Outward				**>35.2 mSv**
Return Path	1E4..1E5 e^-	1500s = 25min	1500s* (1/300)*355mSv/h	>0.5 mSv
	1E5..1E6 e^-	1200s = 20min	1200s* (1/30)*355mSv/h	>3.9 mSv
	1E5..1E4 e^-	≈0s	≈0 mSv	≈0 mSv
Total Return				**>4.4 mSv**
Total resulting Dose				**>39.6 mSv** **>39.6 mGy**
Reported Dose				**1.8 mGy**

Table 2 Determination of the Total Radiation Dose for 4 mm Al shielding

The total dose changes depending on the shielding thickness (and material). From the total dose calculation [4] there result also dose values for further shield thickness'.
The following table shows the total dose in dependency of the shielding. The value of 4 mm is green marked as above.

Shielding [mm Aluminium]	Total Mission Dose [mSv]
0.05	9'175.1
0.1	6'297.3
0.2	4'105.4
0.3	2'999.9
0.4	2'308.4
0.5	1'835.1
0.6	1'503.3
0.8	1'087.3
1	835.5
1.5	485.4
2	290.1
2.5	173.1
3	104.0
4	39.6
5	15.5
6	5.9
7	2.1
8	0.8
9	0.4
10	0.2
12	0.2
14	0.1
16	0.1
18	0.1
20	0.1

Table 3 Total Mission Dose as a function of the shielding thickness

Discussion:
The value of 1.8mGy as published by NASA corresponds in the above table to a shielding of slightly more than 7mm. (For comparison: according to the Table 1 which is calculated for 1969 a shielding of greater 20mm would have been necessary.)
Quantitative information about the radiation shielding of the CM is not known to me. Such shielding is not necessary for flights in Low Earth Orbits up to 500 km, but for flights higher than 1'000 km altitude it is crucial.

Assessment of the radiation shielding of the CM:
The inner structure of the CM consists of an aluminium honeycomb sandwich bonded between sheet aluminium alloy. The outer structure, the heat shield, is made of steel honeycombs. [19] [20]
With this construction technique one can get with little material a high stability.
Areas with low radiation shielding excessively reduce the total shielding.
In summary the above required 7mm shielding may have been well achieved or even exceeded.

5 Effects of Radiation

The influence of radiation is shown in the following table [6], translated:

Dose [Sv]	Radiation effect
0 to 0,5	Without greater diagnostic effort no immediate disadvantageous effects noticeable, but degradation of the immune system
0,5 to 1	Changes in the blood picture, erythema, sporadic nausea, vomiting, very rare events of death
1 to 2	Disadvantageous effects on the bone marrow, vomiting, nausea, bad general condition, about 20% mortality
greater 4	Severe constraints of the general condition and heavy disturbances on the sanguification. The disposition to infections is strongly increased, 50% mortality
greater 6	Besides the named heavy disturbances there appear gastrointestinal symptoms. The survival rate is very low
over 7	almost 100% mortality
over 10	Additional damage of the central nervous system, up to paralyses
over 100	Fast death caused by a malfunction of the central nervous system (sudden death)

Table 4 Effects of Radiation

The natural annual dose is 2.5-4.5mSv.

The optimistically determined mission dose of the previous chapter is according to the above table well in the save area.

6 Determination of the Flight Path

Some points of the flight path of the Apollo 11 mission are exactly indicated in the Mission Report [13], including the velocity vector. With this the flight path can be calculated with help of numerical simulation. So in the end all data including time stamps are available.
In the performed simulation all given points almost exactly correspond with the simulation. The used curves can therefore be regarded as perfect for this consideration.

For the numerical simulation the following differential equation is integrated:

$$\underline{\ddot{r}} = -\frac{\Gamma \cdot M}{|\underline{r}|^3} \cdot \underline{r}$$

with $\underline{r}$: Vector from the centre of the Earth to the space craft
Γ: Gravitational constant: $6.674 \cdot 10^{-11}$ $m^3/(kg \cdot s^2)$
M: Mass of the Earth: $5.976 \cdot 10^{24}$ kg
$\underline{\ddot{r}}$: 2^{nd} time derivative of $\underline{r}$: acceleration vector

The reference system is Earth fixed (not rotating with the Earth): the origin is in the centre of the Earth, the x-axis in the direction of the vernal equinox, the z-axis = Earth axis in the direction of the North Pole and the y-axis results from the right-handed system.

The position of the Earth axis relative to the Sun and the position of the Earth on its orbit is visualised in the following figure:

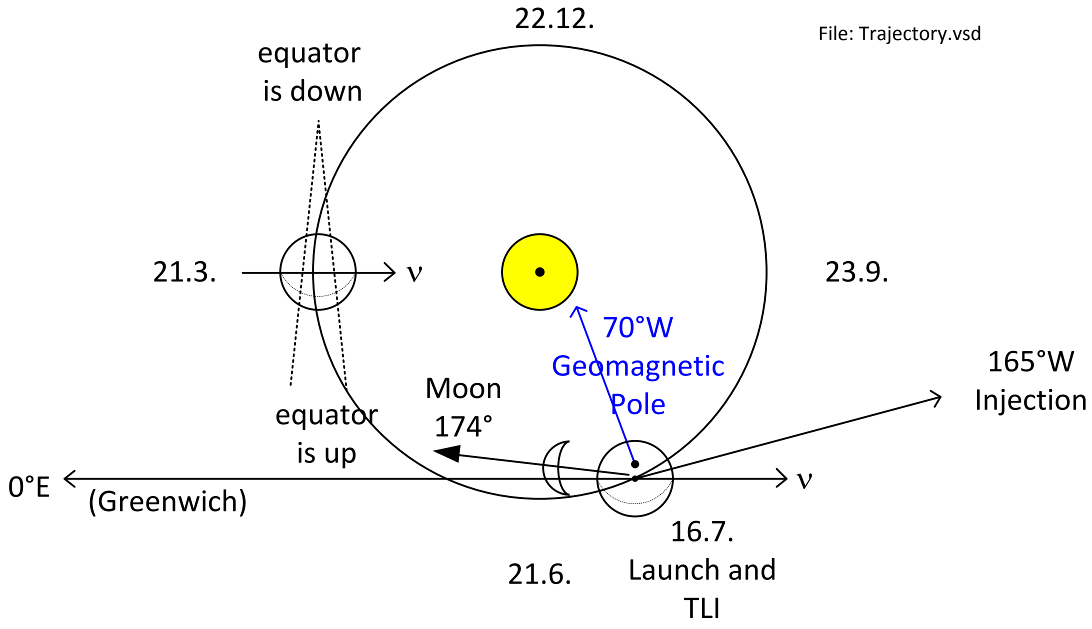


Figure 8 Constellation of Sun, Earth and Moon at TLI of Apollo 11

Figure 8 shows the constellation at TLI (Translunar Injection), i.e. after the acceleration phase behind the Earth: from this point in time the flight goes „in free fall" in direction Moon. The direction of the Moon corresponds already to the one of the reported arrival in a lunar orbit of Apollo 11, at 174° [12][13] (ecliptic) longitude (from vernal equinox ν).
The Sun is shown in yellow in the middle of Figure 8, on the left once again the Earth on March 21st, i.e. at equinox. The inclination of the equator is indicated as well.
The geomagnetic pole was 1969 at (78.5°N, 70°W) [11]. Its direction from the north pole is indicated.
TLI was behind the Earth, seen from the Moon: (10°N, 165°W) [13]. The direction is also indicated.

For a better imagination of the flight trajectory one can take the logo of the Apollo Flight Journal [15]. I have complemented it with directional arrows:

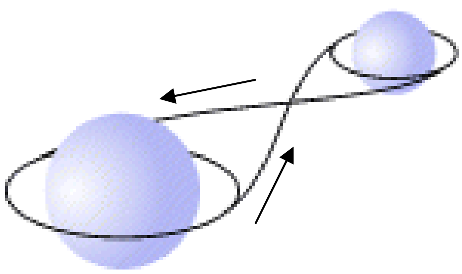


Figure 9 Logo of the Apollo Flight Journal with the Flight Trajectory

The main results of the trajectory calculation are directly worked into chapter 3, specifically in Figure 6 and Figure 7.

For a better understanding of the flight path there are several additional curves shown: first the flight trajectory, as it already has been shown in Figure 6 and Figure 7. The points which have been used for the dose calculation in the electron belt and which are marked with blue circles in Figure 7 are also indicated here with blue circles.

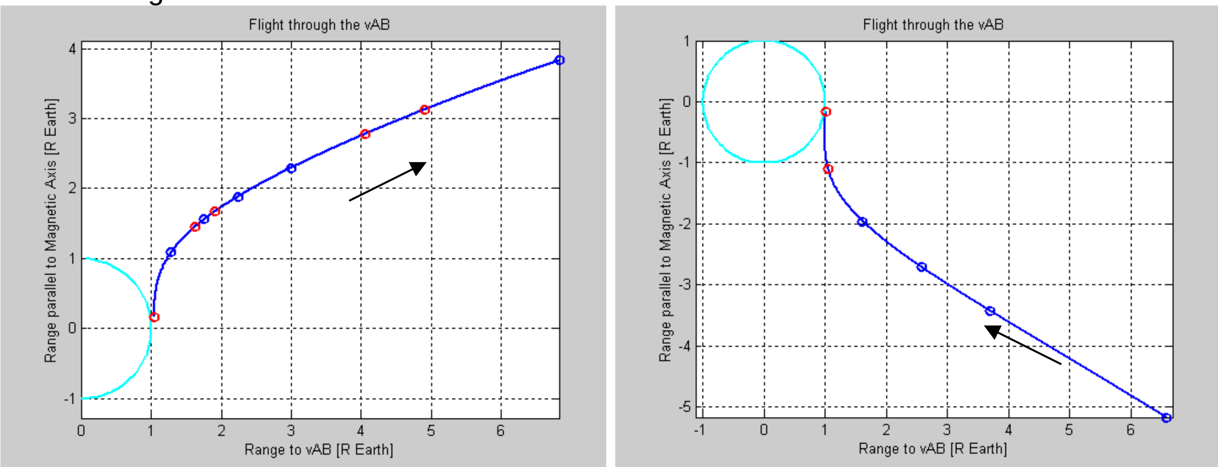


Figure 10 Flight Path in the Geomagnetic Reference System

Now there follow 2 figures in the equatorial and in the ecliptic reference system. The latter corresponds probably the best with our imagination: the Moon was at the approach in the ecliptic, at the departure it was 2° below the ecliptic.

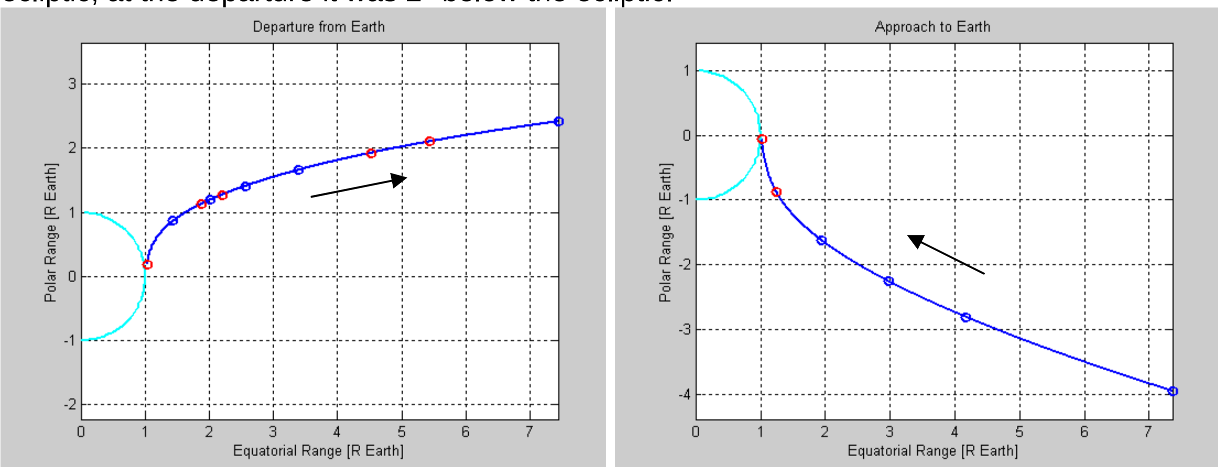


Figure 11 Flight Path in the Equatorial Reference System

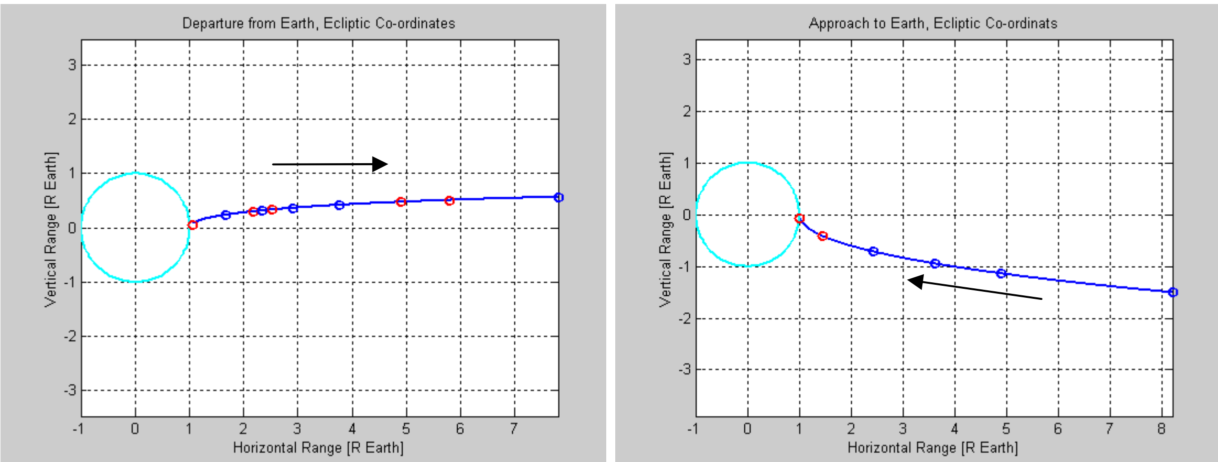


Figure 12 Flight Path in the Ecliptic Reference System

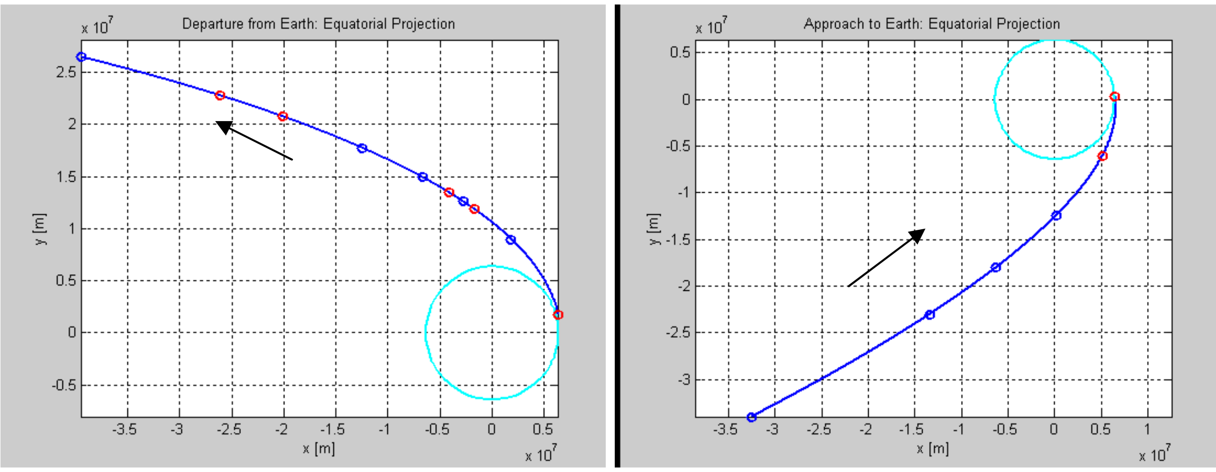


Figure 13 Projection of the Flight Path in die Equatorial Plane

According to the following two figures one can imagine how a rocket during the departure (left) flies as a high jumper over the Van Allen Radiation Belt; during the return flight on the right the same behaviour but down under.

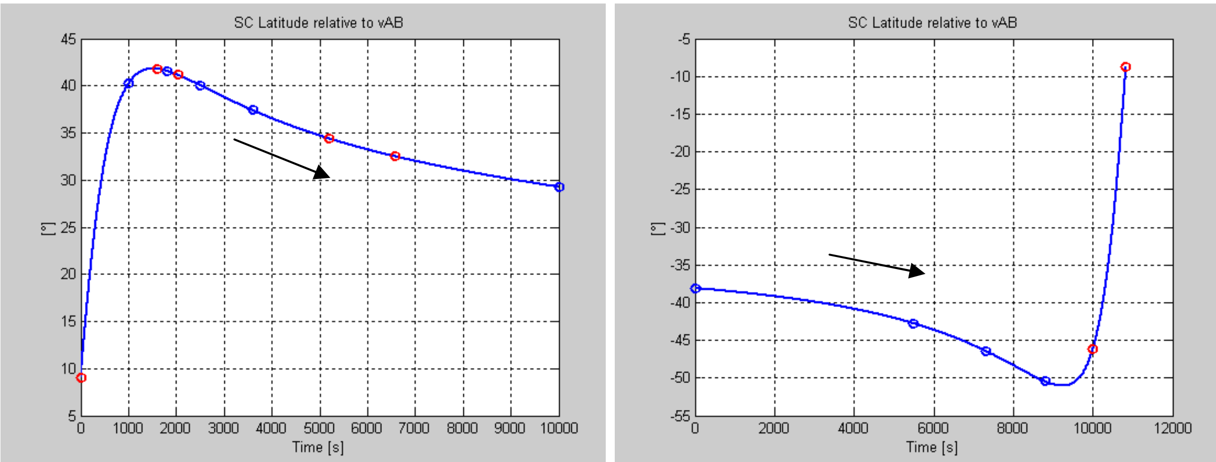


Figure 14 Latitude in the Geomagnetic Reference System

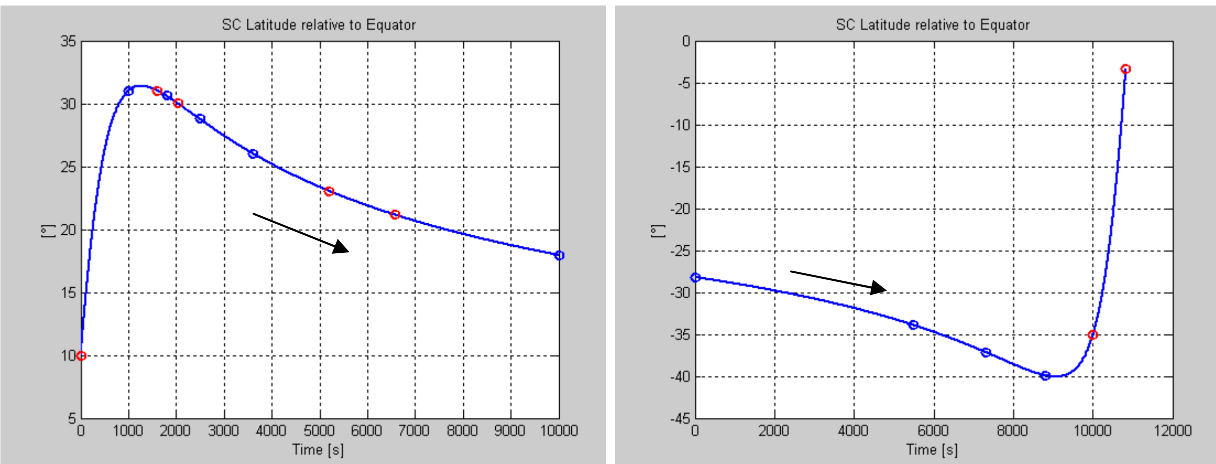


Figure 15 Latitude (in the Equatorial Reference System)

7 Summary and Conclusion

This investigation shows the risk which is taken on a flight to the Moon:
If the Sun suddenly gets active, what can not be predicted, also not for a short time span [lecture of a solar researcher] [16], one is rapidly covered with a health affecting dose.

This substantial risk is confirmed by the following statement on the internet site [7] of ESA *„In the near-term, manned activities are limited to low altitude, and mainly low-inclination missions"*. With other words a lunar mission (or beyond) is regarded as not controllable.

The total dose of the described Apollo 11 trajectory appears very low. It required either a perfectly quiet Sun, i.e. no ionising radiation from the Sun, or a significant radiation shielding. The dose would have (almost) exclusively been caused by the permanent existing free electrons and protons in the Van Allen Radiation Belt. This would have been the normal case in a year of a solar minimum, but in a solar maximum as in 1969 this could have been only temporarily the case.

The used radiation model is a standard for space industry. For the above conclusions it seems to be accurate enough. The possibility that the model produces massively too high values is very unlikely. On the one hand this is in contradiction to new measurements [21], on the other hand the space industry would overestimate the radiation, and this since a long time.

When the Sun is totally or at least almost calm, one can overcome a flight to the Moon and back as shown also with a low shielding without radiation damage. The shielding is only compulsory in the Van Allen Radiation Belt.
The flight path as described in the Mission Report avoids the centre of the Van Allen Radiation Belt in an elegant way. For an even better flyover one would have to turn off from a polar parking orbit. But this would cost more energy.

The maximum operational dose limit for each of the Apollo missions was according to [16] set at 400 rad (4 Gray or over 4 Sv) to skin and 50 rad (500mGy or over 500 mSv) to the blood-forming organs. Further there is reported that in the well shielded Command Module (CM) the crewmen would have received even at a large solar-particle event a dose of 360 rad to their skin and 35 rad to their blood-forming organs (bone and spleen).
This estimation fits indeed perfectly to the above maximum dose values, but it is in contradiction to the physical effect of radiation and shielding: the radiation which passes the cover of the CM is a penetrating radiation[2]. The additional shielding effect of the skin is then almost negligible, so that all organs should receive about the same dose.
All this together with the in general little addressed or even downplayed radiation risk let the Apollo 11 reports look hardly realistic.

[2] The penetrating radiation consists in this context of proton radiation and of Bremsstrahlung, which becomes manifest in gamma radiation.

8 References

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[3] http://www.umweltlexikon-online.de/fp/archiv/RUBradioaktivitaet/Strahlendosis.php → Strahlenbelastung

[4] SPENVIS, ESA's Space Environment Information System, www.spenvis.oma.be.
In chapter 3 and 4 for the year 1969 with „all switches set to Minimum": AP-8 and AE-8 each on solar minimum; Emission of Solar Protons: ESP-PSYCHIC, Confidence level: 50% (minimum value), 4mm Alu sphere, Tissue.

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[9] http://en.wikipedia.org/wiki/Trans_Lunar_Injection

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[18] http://holbert.faculty.asu.edu/eee560/tiondose.html

[19] http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1969-059A

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