MODELING OF COPPER NEEDLE CLUSTERS FROM THE WEST FORD DIPOLE EXPERIMENTS

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ABSTRACT

Clusters consisting of short pieces of thin copper wires have been released during experiments within the West Ford Project in the early sixties on orbits near 3,600 km altitude. The wires should serve as dipole antennas and are also designated as "West Ford Needles". This paper describes the modeling approach for the release of clusters and considers objects with area-to-mass ratios from about 1 m²/kg to 5 m²/kg. The release events are simulated, and the results of a propagation to generate an object population at a reference epoch are presented. The clusters have average geometric diameters between several 100 µm and some millimeters. The contribution to the space debris population in this size range is relatively small.

1 INTRODUCTION

The aim of the West Ford Project was to generate a belt of radio-reflecting dipole antennas around the earth [1], [2], [3]. A high number of small copper needles should be dispensed by two tests. The experiments were launched as piggyback payloads in 1961 and 1963 onboard Midas 4 and Midas 6. (Midas 6 is also designated as Midas 7 due to the launch failure of the sixth Midas satellite [4].) Each satellite ejected one cylindrical dipole dispenser, which contains several hundreds of millions of copper needles. The dispensers were 32 cm long with a diameter of 12.8 cm. The needles were imbedded into a matrix of naphthalene, which evaporates under vacuum conditions [5], [6]. The cylinders should rotate and dispense the needles by the use of centrifugal forces [7]. In the 1963 experiment the dispenser was separated into 5 smaller cylinders, each now rotating more stable, because the diameter of each cylinder is greater than its height. The formation of clusters was an unintended process accompanying the experiments caused by an improper dispensing of the copper needles. During the 1961 experiment no dipole belt was formed due to a malfunction of the dipole dispenser [5], [6]. Based on radar observations of clusters it is estimated that during the 1961 experiment about 40,000 [8] and during the 1963 experiment about 1,000 clusters [9] have been dispensed on earth orbits. The aim of the investigations presented in this paper is to explain why the expected decay of several clusters did not occur [10]. The contribution of the West Ford Needles clusters to the overall debris population is determined depending on the orbital altitude and discussed in terms of object density. These investigations will be used for an upgrade of the "Meteoroid and Space Debris Terrestrial Reference Model" (MASTER) [11], to resolve the debris flux into direction and velocity distributions and to estimate the collision probability.

Tab. 1. Launch epoch and dipole dimensions for both West Ford experiments [5]

Experiment	first	second
Launch date	21. Oct. 1961	9. May 1963
Dipole length	1.78 cm	1.78 cm
Dipole diameter	25.4 µm	17.8 µm

The clusters can be composed of electrically connected dipoles [9]. But also a welding of needles is possible. During subsequently made ground tests it was revealed that the initially performed impregnation of the dipoles with naphthalene under vacuum conditions allows a metal-to-metal contact of the needles before. If clean metal surfaces have contact at vacuum, they can weld together. Therefore the impregnation technique was improved for the 1963 experiment [5]. The assumed composition of a cluster is given in Fig. 1. A cluster may contain compact components consisting of parallel arranged needles, which can reduce the area-to-mass ratio and thus increase the orbital lifetime. A cluster can also contain chains of end-to-end connected dipoles, which are believed to be responsible for the high radar cross section of some clusters.

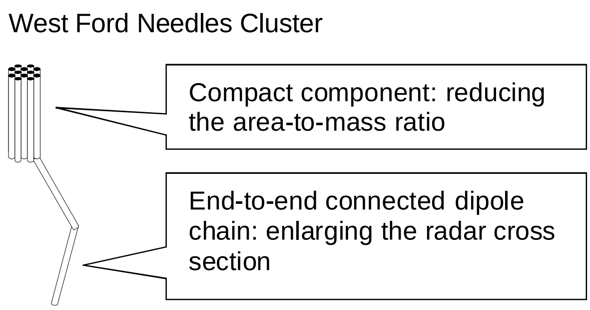

Fig. 1. The assumed composition of dipole clusters

2 MODELING APPROACH

In the following the term "model" refers to the simulation of cluster generation. The model shall be

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

used to generate a cluster population by simulating the dispensing of clusters in space. A propagation of this population shall provide the distribution of clusters at the reference epoch (1. Aug. 1999). Each dispensing experiment is treated as single event. Thus two models have been developed. The models consider only long-lived clusters with area-to-mass ratios smaller than that of a single dipole. Short-lived objects that have been released mainly during the second experiment, like millions of single dipoles and possible clusters consisting only of end-to-end connected dipole chains, are not part of the model. The concept of the model is based on the definition of spherical objects, whose cross-sectional area is identical to the estimated geometric cross-section of a corresponding cluster.

3 MODEL OF THE 1961 EXPERIMENT

The model for the cluster dispensing during the first experiment must meet the requirement of generating varying area-to-mass ratios. Because of the assumed welding of some dipoles, it is likely that bigger clusters contain compact components and have therefore a reduced area-to-mass ratio. This reduction is achieved simply by defining a constant cluster density. Based on the simplified assumption of defining a spherical cluster shape, the area-to-mass ratio is reduced proportional to the reciprocal value of the diameter.

3.1 The Effective Diameter

Data on cluster sizes have been derived from Goldstone radar observations between October 1994 and March 1996. The radar cross sections of small particles were measured, converted into an effective diameter, and presented in Fig. 2 in [8]. Altogether about 400 detections have been measured, which are associated exclusively with clusters from the 1961 experiment. The effective diameter of an object is defined as diameter of a conducting sphere having the same radar cross section as the object [8]. The effective diameter is not necessarily equal to the geometric diameter of an object. The minimum measured radar cross section is 27 mm². For this region Goldstein [8], [12], [13] calculated the effective diameter from the radar cross section by the use of an equation derived from the Rayleigh scattering theory:

$$d_{eff} = \left(\sigma\lambda^4/\pi^5\right)^{1/6} \qquad (1)$$

In Eq. 1 σ denotes the radar cross section and λ the wavelength. With a wavelength of the Goldstone radar of 3.5 cm the effective diameter of the smallest observed cluster is 7.14 mm. For the calculation of the greatest effective diameter the radar cross section is equated with the geometric cross section:

$$d_{eff} = \sqrt{4\sigma/\pi} \qquad (2)$$

With a maximum radar cross section of 466 mm² the greatest observed cluster has an effective diameter of 2.44 cm. The observation data derived from Fig. 2 in [8] are used to determine the run of a curve which describes the cumulative distribution of cluster diameters. The distribution is represented by a simple function, whose type has been found by applying regression analyses to the data. The best fit was achieved by the following type of function:

$$n(>d)/n_0 = c_0 + c_1/d \qquad (3)$$

In Eq. 3 $n(>d)$ denotes the cumulative number of clusters greater than a given diameter d, and n_0 is the total number of released clusters. (For d later the average geometric diameter will be used.) The minimum size of a cluster shall be estimated. The detection of small objects is limited and depends on the distance between object and radar. Thus the smallest observed cluster is not necessarily identical to the smallest existing cluster. In this paper it is assumed that the minimum cluster contains one dipole. In the next step it shall be estimated, which effective diameter a cluster should have if it consists only of one dipole. This estimation is necessary to find out if the size of the smallest existing cluster is in the same order of magnitude as the smallest observed cluster. The effective diameter is calculated considering a randomly-oriented dipole. This consideration is based on the assumption that the dipoles are arranged randomly within a cluster. (Single free-flying dipoles would of course be earth-oriented.) Equations for the calculation of the average radar cross section of randomly-oriented dipoles resp. short wires are given in the literature [14], [15], [9], [16], [17], [18]. In this case equations must be used, which are valid in the Rayleigh region. Such equations are derived in [14]. The special case of a circular polarizing radar is given in [15] and simplified in [9] for the monostatic case:

$$\overline{\sigma} \approx \pi^5 l_{dip}^6 \Big/ \left\{120\lambda^4\left[\ln\left(2l_{dip}/d_{dip}\right)-1\right]^2\right\} \qquad (4)$$

In Eq. 4 l_{dip} denotes the length and d_{dip} the diameter of a dipole. Eq. 4 can also be applied to bistatic radar facilities if the receiving and transmitting antennas are located close together. The comparison with the smallest observed cluster is realized next by calculating the effective diameter of the smallest existing cluster. Replacing σ in Eq. 1 by the average radar cross section of a randomly-oriented dipole from Eq. 4, an expression for the effective diameter of the smallest existing cluster is obtained:

$$d_{eff,\min} \approx 0.45 l_{dip} \left[\ln\left(2 l_{dip} / d_{dip} \right) - 1 \right]^{-1/3} \quad (5)$$

Because Eqs. 1 and 4 both have been derived from the Rayleigh scattering theory, Eq. 5 is an expression which is independent of the wavelength and only a function of the dipole dimensions. With the dimensions of the needles used in the 1961 experiment, given in Tab. 1, the diameter of the smallest existing cluster is calculated to be 0.435 mm. This diameter is 60 % of the effective diameter of the smallest observed cluster and so very close to the detection limit of the Goldstone radar. This closeness justifies the extrapolation of the size distribution function below the observation limit.

3.2 The Average Geometric Diameter

The model requires an estimation of the geometric diameters of the clusters to determine the cross sectional area. This cross section is needed for the calculation of the influence of perturbing forces like the solar radiation pressure and the atmospheric drag on the orbits of the clusters. The average geometric cross section of a randomly-oriented wire can be expressed in relation to the maximum cross section of a cylinder. Provided that the dipole length is much greater than its diameter this relation becomes:

$$A^{*} = A_{av,dip} / \left(l_{dip} d_{dip} \right) = 0.842 \quad (6)$$

In Eq. 6 $A_{av,dip}$ denotes the average geometric cross section of a randomly-oriented dipole. The average geometric diameter of a sphere, representing a cluster which consists only of one randomly-oriented dipole, can be calculated by the use of the average geometric cross section from Eq. 6:

$$d_{av,\min} = \sqrt{4 A^{*} l_{dip} d_{dip} / \pi} \quad (7)$$

Relating the geometric diameter from Eq. 7 to the effective diameter from Eq. 1, a conversion factor of 0.16 can be determined. This factor will be used to estimate the difference between the "apparent" effective diameters (that had been derived from the Goldstone observations) and the "real" geometric diameters of the clusters. The factor will be used in the following to convert the observed cluster sizes into average geometric sizes. Thus the maximum geometric diameter results from multiplying the maximum effective diameter with this factor:

$$d_{av,\max} = 0.16 d_{eff,\max} \quad (8)$$

Using the maximum observed radar cross section and Eq. 2, a maximum geometric diameter of 3.90 mm is calculated.

3.3 Modeling Parameters

The clusters have probably been formed, when clumps of needles left the dipole dispenser. The authors assume that this happened during or a short time after the ejection of the dispenser from the satellite and the evaporation of the naphthalene. Thus the cluster formation is treated as single event. No information about the exact date of ejection has been found in the literature. So the launch date of the satellite was taken as reference here. The orbital elements are given in the Two Lines Elements (TLE) catalog and summarized in Tab. 2. Due to a malfunction, the dispenser did probably not rotate after the ejection [5]. So no additional velocities were imparted to the clusters. The mass of the smallest cluster consisting of one dipole can be calculated with the given density of copper (8,960 kg/m³). The mass of the biggest cluster is determined with the number of dipoles included in the cluster. Considering a constant density and a spherical volume of the clusters, the number of dipoles in the biggest cluster is:

$$n_{\max} = m_{\max} / m_{\min} = \left(d_{av,\max} / d_{av,\min} \right)^{3} \quad (9)$$

In Eq. 9 m denotes the mass. The subscripts "*min*" and "*max*" refer to the smallest resp. biggest cluster, considered by the model. The mass of the biggest cluster can be calculated by multiplying the mass of one dipole with the maximum number of dipoles from Eq. 9. With the mass and the already known geometric cross sections it is possible to determine the most important model parameter, the area-to-mass ratio, which is mainly needed for the correct estimation of the influence of the solar pressure on the cluster orbits. Applying the concept of constant cluster density on the different cluster sizes, given by the size distribution function Eq. 3, results in a spreading of area-to-mass ratios between the values of the smallest and biggest cluster. I. e., every cluster has a different area-to-mass ratio depending on its geometric diameter. The cluster density is here defined as the density of one randomly-oriented dipole with the average geometric diameter from Eq. 7:

$$\rho_{cl} = 6 m_{\min} / \left(\pi d_{av,\min}^{3} \right) \quad (10)$$

This density is defined to be constant for all cluster sizes.

The cumulative size distribution function contains three parameters. These are the total number of dispensed clusters n_0 and two regression coefficients c_0 and c_1. An estimation for the total number of clusters is given in [8]. The coefficients have been found by applying a regression analysis to the data of measured cluster sizes, which have before being converted into geometric diameters. Using the size distribution function it is possible to estimate further parameters which result from the sum of all clusters. These are the total mass of copper that has been released in form of clusters m_{tot} and the total number of needles included in all dispensed clusters $n_{dip.tot}$. A summary of the model parameters is given in Tab. 2.

4 THE 1963 MODEL

The second model is similar to the 1961 model. The concept of defining a constant cluster density for the generation of varying area-to-mass ratios has been adopted. It is likely that less clusters including welding connected dipoles have been formed (compared to the total number of released clusters) due to the improved impregnation technique. Therefore it is assumed that more clusters consisting of end-to-end connected dipole chains were created. Such chains have area-to-mass ratios, which are comparable to that of single dipoles. Thus their orbital lifetime is low. Because of this they are not considered by the model. Nevertheless also during the 1963 experiment clusters should have been produced which contain compact components. The reason for this assumption is that several long-lived clusters have been observed, which are now registered in the TLE catalog. To simplify the numerical implementation of the model the same value for the cluster density has been chosen as for the 1961 model. Due to the lack of data about of cluster diameters the same type of size distribution function was used as in the 1961 model. Also for the 1963 experiment it is assumed that clusters have been formed during or a short time after the ejection of the dispenser from the satellite. Like for the 1961 model the cluster formation is treated as single event. The orbital elements of the components of the dipole dispenser are given in [19] and are summarized in Tab. 2. According to [5] the rotation frequency of the dispenser is 8 revolutions per second. Thus the maximum additional velocity is calculated to be 3.2 m/s. The model parameters are estimated in a similar way as for the 1961 model. The difference is only that for the 1963 model the cluster density and for the biggest cluster also the area-to-mass ratio of long-lived clusters are used as input parameters. Estimations of the area-to-mass ratios for clusters with extended orbital lifetimes and the number of released clusters are given in [9]. These parameters have been derived from radar observations. From these inputs the values for parameters like the average geometric diameter etc. are calculated and summarized in Tab. 2.

Tab. 2. Modeling parameters and orbital elements for both West Ford experiments

Modeling parameters		Experiments 1961	1963
Minimum cluster	$d_{av,min}$ [m]	0.696E-3	0.549E-3
	m_{min} [kg]	0.808E-7	0.397E-7
	A/m [m²/kg]	4.71	5.97
Maximum cluster	$d_{av,max}$ [m]	3.90E-3	3.28E-3
	m_{max} [kg]	0.142E-4	0.845E-5
	n_{max} [-]	176	213
	A/m [m²/kg]	0.841	1.00
Clus. density	ρ_{cl} [kg/m³]	0.457E+3	
Cumulative size distribution	c_0 [-]	- 2.174E-1	- 2.011E-1
	c_1 [m]	8.475E-4	6.598E-4
	n_0 [-]	40,000	1,000
Sum of all clusters	m_{tot} [kg]	0.597E-1	0.822E-3
	$n_{dip,tot}$ [-]	739,000	20,700
Max. add. velocity [m/s]		0	3.2
Orbital elements			
Event epoch		21.10.61	12.05.63
Semi-major axis [km]		10,004	10,020
Eccentricity [-]		0.013	0.004
Inclination [deg]		95.89	87.35
R. A. of asc. node [deg]		308.35	229.00
Argument of perigee [deg]		18.0	68.2

5 RESONANCE EFFECTS

Single dipoles (and some of the clusters) have relative high area-to-mass ratios. Thus the solar pressure changes their orbits and can be used to reduce the orbital lifetimes. Orbits were chosen for the West Ford project where the solar pressure lowers the perigees continuously, until the dipoles reach the upper layers of the atmosphere and re-enter [19], [20], [21], [22]. An orientation of the orbit is reasonable for which the direction of the sun lies parallel to the orbital plane and perpendicular to the major axis. By utilizing the perturbations of the second harmonic the orbit's state is continuously changed to maintain the desired orientation to the sun. This condition is called "resonance" and depends for circular orbits only on the semi-major axis and the inclination:

$$a_{nom} \approx r_e \left[5 \left(1 - 2\cos i - 5\cos^2 i \right) \right]^{2/7} \qquad (11)$$

In Eq. 11 a denotes the semi-major axis, r_e the radius of the earth (6,378 km) and i the inclination. The subscript "*nom*" refers to the nominal resonance line. Eq. 11 is based on Eq. 101 in [22] neglecting the eccentricity. Due to additional changes of the orbital elements by the solar pressure the initial adjusted change rate of the orbit orientation cannot be retained. Therefore an average change rate was determined leading to a greater semi-major axis as initially estimated with Eq. 11 [22]. Considering the area-to-mass ratios a "resonance band" of about 300 km width is given for objects with 5 m²/kg. The center of the band is located some kilometers above the nominal resonance line calculated with Eq. 11 [21], [22]. This band was missed for the 1961 experiment. Midas 4 reached an improper orbit due to a roll-control failure shortly after launch [4]. According to the orbital data, given in [21], it can be assumed that the initially planned orbit should have an inclination close to 90 deg. The deviations of the planned and actually reached orbits from the nominal resonance line are given in Tab. 3.

Tab. 3. Comparison of initially planned with the actually reached orbit for the first West Ford experiment

1961 experiment	i [deg]	a [km]	$a - a_{nom}$ [km]
Planned orbit	90.00	10,178	76
Actual orbit	95.89	10,004	- 516

6 NUMERICAL RESULTS

6.1 Orbital Lifetimes

Numerical simulations for the 1961 experiment show that the orbital lifetime of clusters is very long. The maximum possible area-to-mass ratio (having probably the lowest orbital lifetime) can be calculated to be 5.6 m²/kg by using the maximum cross section of a single dipole. The results show that this object will not decay before the reference epoch. If the orbital elements at the time of dispensing would be modified to satisfy the resonance condition, the lifetime would be much shorter. Substituting the inclination and semi-major axis by the values of the initially planned orbit from Tab. 3 results in a lifetime of 3.6 years. Similar simulations have been made for the 1963 experiment. Due to the smaller dipole diameter the maximum possible area-to-mass ratio is 8 m²/kg. This object decays within 1.5 years, because the resonance condition is satisfied. The model for the clusters starts with 6 m²/kg. Such objects have an orbital lifetime of 2.1 years. The resonance ends near 2.5 m²/kg with lifetimes of 7.1 years. The simulation of objects with smaller area-to-mass ratios shows an oscillation of the perigee altitude. Also these objects can re-enter. This happens for example if the lowering of the perigee coincides with a period of high solar activity. In this case the clusters can be decelerated by the expanding atmosphere. From the initially 1,000 generated clusters 212 are still in orbit at the reference epoch according to the simulations.

6.2 Spatial Density

The spatial density was calculated for a reference epoch of the 1. August 1999. In Fig. 2 the spatial density is given for the 1961 experiment. The distribution of clusters is limited to orbital altitudes between 1,800 km to 5,400 km with a maximum density near 3,600 km.

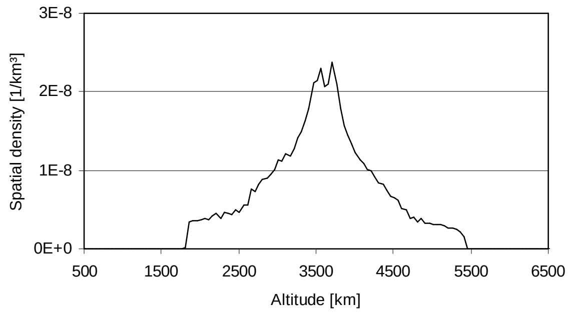

Fig. 2. The spatial density of clusters from the 1961 experiment versus orbital altitude at the reference epoch (1. Aug. 1999)

The spatial density for the 1963 experiment is given in Fig. 3. The clusters are distributed over a wider altitude range and appear also on very low orbits of about 600 km. The maximum of the spatial density lies also near 3,600 km. The spatial density is lower as for the 1961 experiment due to the lower number of clusters and their high decay rate.

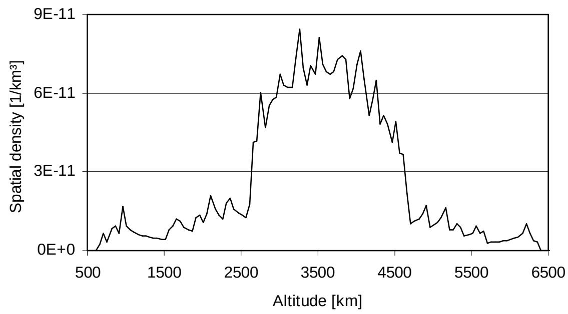

Fig. 3. The spatial density of clusters from the 1963 experiment versus orbital altitude at the reference epoch (1. Aug. 1999)

The spatial density of the clusters compared with other contributions to the space debris environment is given in Fig. 4. The presentation is limited to diameters greater than 1 mm. The fragments, slag particles and TLE objects (meaning objects of the TLE catalog, which have not been generated by fragmentation events) appear on all orbital altitudes. In opposition to that, NaK droplets and clusters are limited to special altitude ranges. Fig. 4 shows the spatial density of clusters calculated from the sum of both experiments as bold line. Their contribution to the space debris population is about 3 or 2 orders of magnitude smaller than for fragments or slag at 3,600 km altitude.

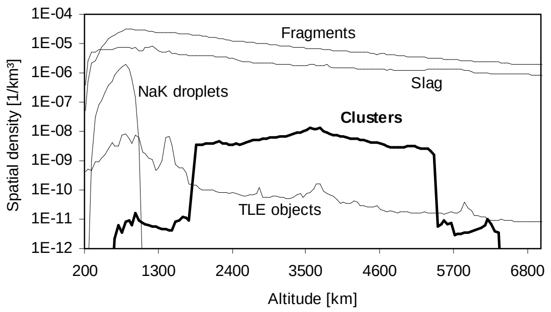

Fig. 4. The spatial density of orbital debris greater than 1 mm versus orbital altitude including the clusters from both West Ford experiments at the reference epoch (1. Aug. 1999)

7 CONCLUSIONS

Two models have been developed to describe the unintended dispensing of clusters by the two experiments of the West Ford Project. The basis for the investigations is the definition of a constant cluster density. Both models have similar parameters and consider clusters with area-to-mass ratios from about 1 m^2/kg to 5 m^2/kg. The biggest simulated clusters include roughly 200 needles. The clusters have average geometric diameters between several 100 µm and some millimeters. The contribution to the space debris population in this size range is relatively small. The total mass of all clusters in space at the reference epoch is estimated to be 60 g. The total number of clusters is roughly 40,000 consisting of altogether 750,000 needles. It can be expected that most of the clusters from the 1961 experiment will stay on orbit for a long time.

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