2.3
Radar Detection of Spherical Targets

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1. Principles of RADAR

Electric currents are induced in a conductive object when it is illuminated with radio energy from a transmitting antenna. These currents cause the object itself to act like a secondary antenna and re-radiate energy. Some of this energy is directed back towards the transmitter and is said to be reflected. A receiving antenna can then collect it, and the measured time delay of this "echo" can be used to calculate distance based on the fact that radio waves travel at the speed of light. When the transmitting antenna is shaped to radiate the energy into a narrow beam it becomes possible to discriminate both target range and target direction. This is the basic principle of RADAR (RAdio Detection And Ranging).

In practice the same antenna is generally used for transmitting and receiving and is switched rapidly between these modes, so that the energy is emitted in a short pulse after which the radar listens for echoes from targets and this duty cycle is repeated typically hundreds of times per second while the antenna rotates to continuously scan a large volume of the atmosphere. Roughly speaking, the angular width and angular height of the emitted beam, and the pulse length, together define a resolution cell which is a minimum volume having dimensions of azimuth, altitude and range within which the radar will not discriminate between two adjacent targets.

Types of targets divide broadly into area targets, volume targets and point targets, the echo from each having a different range dependency. Area targets are extended two-dimensional surfaces such as large areas of surface terrain; the strength of returned echo varies like the cube of the distance. Volume targets are three-dimensional regions of echo, large in relation to the resolution cell dimensions, and with some radar transparency, such as rain clouds; and their strength of echo varies like the square of the range. Point targets are the type of targets of interest to most radar operators, discrete objects with echoing areas that are not large relative to the resolution cell dimensions, such as aircraft, birds etc., and the strength of echo from these targets varies like the 4th power of range, which appears in the denominator of the simplest form of the primary radar equation[1] for average received power P_r as

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[1] Secondary radar (SSR), widely used in Air Traffic Control alongside primary radar, does not detect echo but employs the method of triggering radar transponders whose replies encode aircraft identification and barometric height readings. SSR detection probability therefore varies only like the inverse square of range instead of the inverse 4th power.

$$\overset{\text{---}}{P_r} = \frac{P_t\, G^2\, \lambda^2\, \sigma}{(4\,\pi\,)^3\ R^4} \qquad 1$$

where P_t = transmitted power, G = antenna gain, λ = wavelength, R = range to the target, and σ is a parameter called the *Radar Cross-Section* of the target.

2. General Definition of Radar Cross-Section

Technically Radar Cross-Section (RCS, or σ) is the ratio of radiated power density intercepted by a target to the power per unit solid angle backscattered to the receiving antenna by the target, so it is a measure of the efficiency with which a target echoes radar energy back to the radar receiver. This efficiency depends on shape, size, material composition and other factors that vary widely between different types of target. Therefore in order to compare dissimilar targets it is useful to express their efficiency in terms of the projected cross-sectional area of a perfectly conducting sphere which would return the same power to the same receiver in the same conditions. This equivalent area is the RCS and is expressed in square metres.

In general RCS is determined by projected area and by the directivity (both of which are dependent on the bulk geometry of the object) and the reflectivity (dependent on the material composition and/or small-scale surface geometry of the object). As a matter of general practice, and for most of the purposes of this study, UAP detections can be considered to involve point targets in the equivalent optical region of the RCS diagram in Fig.1, where RCS is a constant independent of the wavelength and where probability of detection varies simply like the 4th power of the range. But as discussed below there are special circumstances in which range and/or target diameter is not large with respect to wavelength and where the RCS of a spherical target varies according to wavelength.

3. General RCS of a Sphere

The RCS of a sphere is in most cases especially simple (Goodrich et al., 1961). If the diameter is large compared to the operating wavelength then the RCS of a smooth reflective sphere is just its projected geometrical area, or $\sigma = \pi r^2$**,** and this is constant with regard to wavelength and with regard to any linear polarisation. Thanks to spherical symmetry everything also stays constant regardless of aspect. For these reasons spheres are often used as radar calibration targets.

Another simplification allowed by spherical targets is that tracking errors will be negligible. Because an echoing target acts as an antenna re-radiating intercepted power, its radar *out*put has its own near- and far-field properties and a radiation pattern related to its size and shape. For large and complex targets the phase differences between wavefronts coming from different parts of the target can add or subtract in complicated ways to shift the phase centroid away from the geometric centre of the target - even outside the physical target volume. This is called a 'glint' error, which can be significant for tactical tracking radars in particular. But in the case of a smooth sphere there is no glint or tracking error, as the phase centroid always coincides with the geometric centre.

As already mentioned, in the far-field or 'optical' region of the RCS diagram in Fig.1, where $\lambda <<$ range and $\lambda <<$ radius, RCS is constant. However when the circumference of the sphere falls below about 10λ, then the response is in the Mie resonance region of the diagram and RCS can fluctuate increasingly widely as the circumference approaches the wavelength. Finally, where $2\pi r/\lambda$ falls below 1.0 we enter the Rayleigh region, which describes the case for spheres that are small in relation to the wavelength and here the RCS is strongly and linearly wavelength-dependent (like the 4th power). This is the part of the diagram usually appropriate to weather radar detection of raindrops and hail.

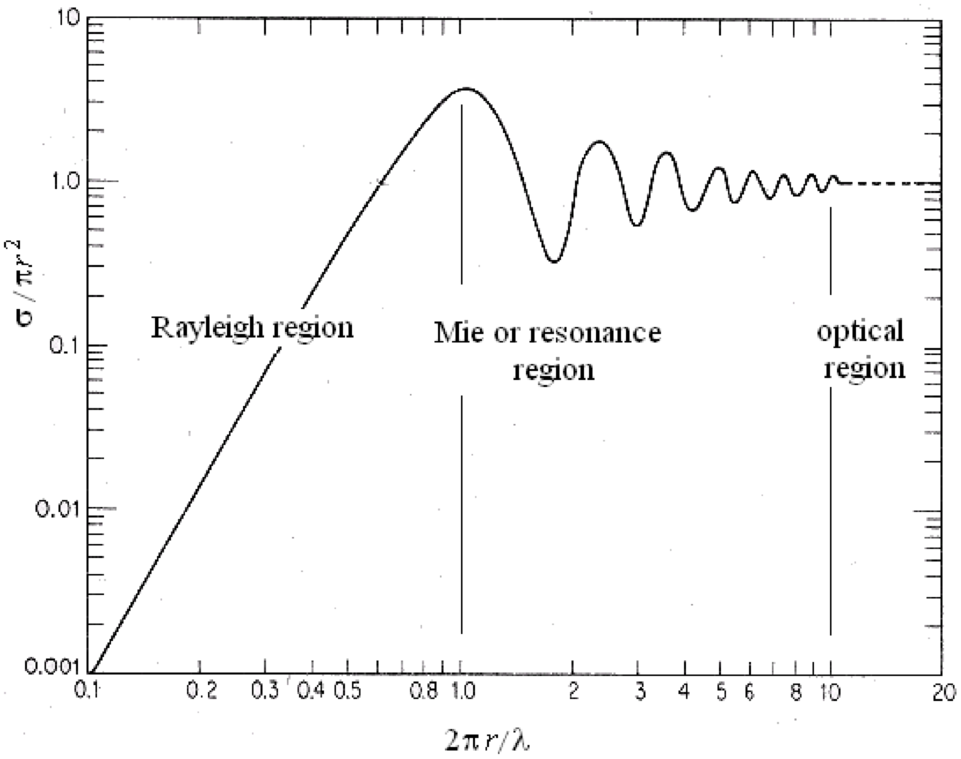

Figure 1. The Radar Cross-Section Diagram

4. RCS of a Sphere in the Mie Region

As described in Section 3, in the Mie or resonance region the far-field RCS equation breaks down. This is mainly due to interference caused by "creeping waves". Whilst most of the radar energy returned from a sphere is due to specular reflection at the point nearest to the antenna, there is an added contribution when the radar wavelength is near the target circumference (Fig 2). Some radar energy follows the surface of the sphere and "creeps" all the way around its shadowed side to be backscattered towards the receiving antenna. But because of phase differences these two components of the radar return do not always add constructively. Instead interference produces a series of peaks and troughs, so that where $\lambda = 2\pi r$ the RCS oscillates, up to a peak of 4 times the far-field value rising from an adjacent minimum of 0.26 times the far-field value. In other words a change of less than a factor 2 in either the target radius or the radar wavelength can change RCS by a factor of about 15.

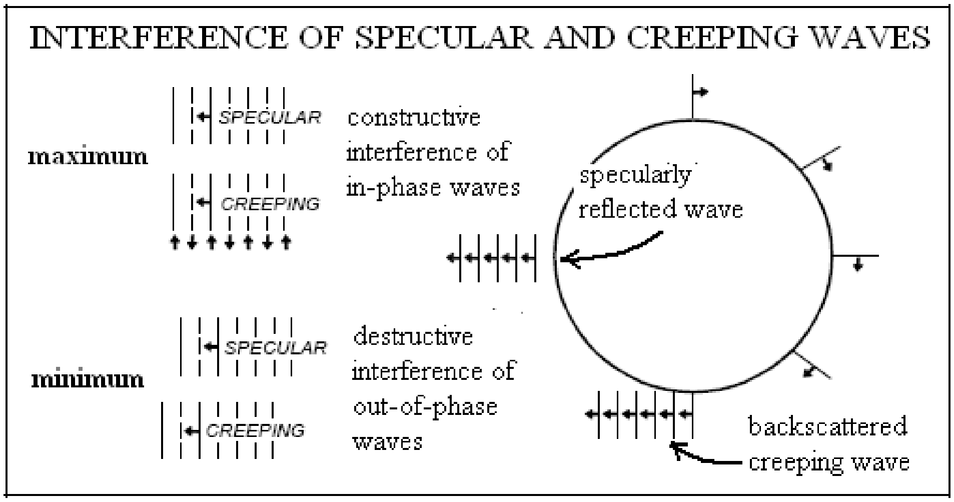

Figure 2. Specular and Creeping Waves on a Spherical Reflector

5. Polarisation

Polarisation of a simple radio wave is defined by the orientation of the plane of the electric vector, which is rotated 90° relative to the plane of the magnetic vector. Electrons in a resonating target undergo an induced oscillation in this plane when the energy is absorbed by them, acquiring an electric dipole moment that varies at the frequency of the incident wave, and the oscillating charge in turn acts as a secondary transmitting antenna to return an "echo". By (in effect) rotating the entire radar antenna the designer can choose the plane of radar polarisation to suit different applications. Most radar applications use horizontally polarised waves. For some applications the output is elliptically polarised to varying degrees (as described below), or occasionally cross-polarised. Polarisation losses caused by these different modes are of considerable importance for determining RCS. Some of these losses are unwanted, others are created by design.

Unwanted polarisation loss occurs because most surveillance radar is horizontal plane-polarised in order to optimise detection of horizontally extended edges and cylinders. This direction suits the typical orientation of most targets - aircraft, ships, coastlines etc - needing to be detected in the air or at sea. Horizontal linear polarisation is also often used in weather radars (such as the WSR-88D widely-used in the US NEXRAD network) to maximise echo from raindrops, the reason being that they are flattened by aerodynamic compression forces during their fall. But some target components are narrow vertical cylinders and edges - such as masts, funnels and rigging on ships, or tail fins on aircraft - and these shapes incur polarisation loss because they reflect only the parallel (vertical) component and so give poor echoes for horizontally polarised radars (Wiley, 1952; Briggs, 1998).Similarly, horizontally plane-polarised radar might be relatively inefficient at tracking missile launches, for example, if the typical target orientation is perpendicular to the plane of polarisation, so the output of a dedicated launch tracking radar might be chosen to be vertical plane-polarised.

In these cases the objective is to minimise polarisation loss in order to optimise the detection of certain targets. But in other cases the design goal is to *maximise* polarisation loss in order to suppress echoes from certain targets, especially for rejection of weather clutter in ATC and defence surveillance radars by the use of non-linear polarisation.

Weather clutter is very largely caused by echo from near-spherical water droplets or hailstones, so for this reason circular or elliptical polarisation is used. This is created by splitting the output electric vector into two equal vectors, rotating one through 90° and introducing a 1/4 wave phase delay with respect to the other, with the effect that the resultant electric vector rotates as it progresses down the axis of propagation. This rotation can be either anticlockwise or clockwise with respect to the direction of propagation, described as left-handed or right-handed respectively.

The clutter suppression effect of this technique depends on the facts that the direction of polarisation of the radar wave is inverted through reflection and that an antenna emitting signals of one handedness will only receive signals of the same handedness, rejecting signals of oppositely-handed polarisation. Reflections of right-circularly polarised signals from smooth spheres are returned efficiently to the receiver as *left*-circularly polarised echoes, so the radar is blind to them; whereas echoes from complicated targets such as aircraft or ground structures undergo random numbers of multiple reflections before bouncing back to the receiver and thus arrive having enough of the original handedness to give a usable signal. This technique can reduce the RCS of a near-spherical raindrop by 15-30dB (up to 1/1000) whilst reducing typical aircraft RCS by only 5-7dB (Mao, 1988) or "complicated targets such as ships and aircraft" (Briggs, 1998) by as little as 3dB (1/2), improving the differential visibility of targets in weather by a factor of several hundred.[2]

If raindrops were perfect spheres then simple circular polarisation would be a still more effective clutter suppressor than it is, but they generally are not perfect spheres. Fortunately the phase and amplitude relationships of the component wave vectors can be tailored to produce elliptical polarisations. Elliptical polarisation theoretically can improve the rejection of weather clutter, but different types of raindrop have different ellipticities and matching the output to spheroids with variable axial ratios in the region 0.94 - 0.99 (Skolnik, Intro p.505) is a delicate task. Moreover the degree of ellipticity of the radar polarisation changes as the beam penetrates into the rain because of random phase shifts due to scattering, and the shapes of raindrops themselves may vary from place to place within the same weather system, so that reacting to rain clutter effectively needs adaptive polarisation and complex algorithms.

The use of polarisation designed to suppress weather has implications for the effective RCS of spherical targets in general.

6. General Practical Effects with Typical Radar Wavelengths and Polarisations

Some wavelengths and other characteristics of various civil and military radars commonly used for air traffic control (ATC), defence surveillance and targeting are listed in Table 1. As explained in Section 3 the RCS of a sphere is sensitive to the ratio of wavelength to radius. Where $\lambda <<$range and $\lambda <<$radius we are in the optical or equivalent far-field region of the RCS diagram, where $\sigma = \pi r^2$ and returned signal strength will vary smoothly as the 4th power of the range. The boundary of this region occurs where the circumference of the sphere is more than about 10 times the wavelength, or, to put it

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[2] A technique called linear cross-polarisation can also be used but is not so effective.

differently, where the diameter of the sphere is about 3.2 times the wavelength.

From Table 1 (adapted from Cole, 1985) we can see that for a range of civil/military ATC and surveillance radars this optical case will apply for spheres larger than about 0.5m in diameter (32 - 74cm). Below this size (down to the Rayleigh limit) the Mie resonance case will apply and RCS will fluctuate nonlinearly. For some long range ATC and defence radars the boundary will lie at about 1.6m.

Typical wavelength	Operational role	Characteristics
8mm	Airfield Surface Movement Indicator (ASMI) Infantry manpack	very high resolution for detecting aircraft, ground vehicles and personnel on the airfield portable high-resolution tactical radar for battlefield use
3cm	Mobile security Precision Approach (PAR) Airfield Control (ACR) Gunlaying & tracking Airborne Intercept (AI) Weather radar Marine radar	for area security and military tactical vehicles guides a/c onto glide path and to touchdown guides a/c onto PAR or ILS often mobile, tactical target acquisition and following nose-mounted target-following for air weapons guidance detection of volume precipitation seaborne navigation and anti-collision
6cm	Weather radar	detection of volume precipitation
10cm	Weather radar ATC TMA ATC long range Defence Tactical Defence Search	detection of volume precipitation surveillance of ATC terminal areas, guidance of a/c to runways surveillance of air routes out to ~200nmi transportable, tactical air support and recovery to base, anti-jamming detection of hostiles and direction of interception, anti-jamming, usually with height-finder
23cm	ATC long range Defence Tactical Defence Search	surveillance of air routes out to ~200nmi transportable, tactical air support and recovery to base detection of hostiles and direction of interception, anti-jamming, usually with height-finder

50cm	Long-range ATC	surveillance of air routes out to ~200nmi

Table 1. Wavelengths and Other Characteristics of a Range of Civil and Military Radars

Close to these critical values where the largest Mie resonance fluctuation is to be found it might sometimes occur that multiple radars of different types with operating wavelengths differing by a factor of about 2 (as is the general case in Table 1) might encounter a differential in effective RCS of about an order of magnitude (see Section 3, Fig.1). In practice this means that if the probability of detection of a ~1m sphere is about 90% by a long range L-band *en route* ATC radar then the probability of detection of the same target by an S-band terminal area radar might be only around 10%, or *vice versa*.[3]

A further factor determining RCS is polarisation, as discussed in Section 5. ATC radars in particular require weather clutter suppression. Circular polarisation will cause a designed polarisation loss for spheres of all radii, but for a given r/λ the loss will be smaller the larger r becomes, as increasing radius of curvature of the surface at the specular point approximates a plane reflector (in the limit of a sphere of infinite radius). If non-circular elliptical polarisation is in use, an echo from a perfectly spherical UAP would be rejected at the receiver with somewhat lower efficiency than elliptical raindrops (in terms of dB-down per unit RCS) and might have some added super-clutter visibility on this account. Of course one can only speculate about the true sphericity or otherwise of hypothetical radar-reflective UAPs .

Another type of clutter suppression necessary for most applications is MTI, or Moving Target Indication, which in its simplest form compares pulse-to-pulse phase shifts in the echoed signal to measure small changes in target range (on the scale of a fraction of a wavelength, i.e. typically millimeters) and uses a filter to reject targets with phase shifts above a certain value. In this way permanent clutter due to ground reflections can be eliminated from the display. A side effect is that stationary airborne targets, or moving targets in certain radius turns that happen to preserve constant echo phase, might also be rejected. These problems of MTI "blindness" are not generally very important, but might occasionally be, especially when considering older radar systems involved in historical incidents.

Contrarily, certain targets of complex shape which are stationary in the sense of having no bulk displacement might rotate, either bodily or in part, and present a varying aspect to the radar, such that phase shifts defeat the MTI filter. Thus a stationary target, such as a hovering helicopter, may still appear on the display with MTI switched on.[4] In a similar

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[3] Assuming equivalent conditions, i.e. that the target lies at the same fraction of maximum effective range from both radars, and neglecting factors other than wavelength.

[4] Sophisticated modern MTI (often known as MTD for Moving Target Detection) uses a bank of Doppler filters to examine the Doppler content of returned signals and in this way is able to discriminate and control more types of clutter echo. For example, a reflector such as a wind-blown forest on the side of a hill may have zero bulk displacement yet contain a spectrum of non-zero radial speeds which can defeat simple MTI cancellation. MTI will thus not rid the radar screen of this permanent clutter. But Doppler MTD can analyse these spectra and the filters can be "tuned" to recognise and eliminate them whilst preserving wanted "stationary" targets with different Doppler signatures, such as hovering helicopters.

way, an aircraft on a constant radius course which might otherwise be filtered from the screen due to to MTI "phase blindness" may bank or yaw and return phase-shifted echoes. Clearly, in the case of helicopters and fixed wing aircraft such an MTI "flaw" tends to be quite useful for ATC purposes. But evidently a truly spherical target whose aspect variation is zero will not benefit from it, and therefore we can say that spherical targets may in general tend to have a slightly reduced probability of detection in certain marginal situations (but see Section 8).

7. Material Composition

Material composition has a dramatic effect on RCS of all targets. The radar echo depends on induced charge motions in the target and RCS is calculated as a ratio of the efficiency of a perfectly conducting sphere. But not all types of objects in the air are perfectly conducting, or even conducting at all.

i) solids

Solid spheres made of nonconductive materials will generally have an RCS of approximately zero. Such types of object would include neoprene or polyethylene balloons (neglecting payload equipment which may return an echo). However, balloons with metallised fabrics are sometimes used for radar callibration and similar purposes, and would return an efficient echo subject to all the considerations previously outlined. If an ordinary weather balloon should be wet, or iced in severe cold, then it too may acquire a small RCS.

Conversely, conductive metal spheres which are inherently efficient reflectors might be coated with radar-absorbent paints (a well-established technology dating back to the 1950s), or with high-tech metamaterials,[5] and might as a result have a negligible RCS.

ii) aggregates

On the other hand a target that is not even a solid can be a highly efficient radar reflector, provided it permits the induction of radiating currents. For example a dispensed cloud of very fine wires each a few cm in length can be as effective as a solid sheet of steel in hiding an aircraft from enemy radar, and similar types of "chaff" and "window" have been used to decoy and confuse radars since WWII. A cloud of such reflectors might initially behave for radar purposes somewhat like a compact blob or ribbon, drifting down under gravity and slowly dispersing. But most aggregate wind-dependent targets of this type would be unlikely to behave like airborne spheres for any length of time.

Clouds of suspended water droplets, or ice in the form of hail pellets or crystals, are of course routinely detected by radar. Individual droplets and hail pellets may behave as spherical resonators generally in the Rayleigh scattering region of the RCS diagram. These types of natural precipitation do not normally aggregate in spheroidal forms.

Considering clouds of individual echoing elements on a smaller scale, conductive metallic particles or dusts could form temporarily suspended windborne clouds. Insofar as such reflectors are detectable (an excited resonance depends on the ratio of particle size to wavelength) they would in general tend to behave like natural precipitation, being in the

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[5] Microwave metamaterials are relatively new technology, at least in the white world, and practical applications may be some time away (see Section 8.iii) (Gao, 2005; Varga, 2004)

Rayleigh scattering region for all purposes with an RCS linearly proportional to the 4th power of the radius (see Section 3, Fig.1). Again there seems to be no reason for such particles to form stable spherical aggregations.

There is however the possibility that dielectric dusts may be involved in the shaping of some little-understood types of natural atmospheric plasma related to "ball lightning", so certain types of targets could perhaps be composites, of dusts held together by - and themselves modifying - the charge distribution inside compact plasmoids, to which we now turn.

iii) plasmas

On a still smaller scale than dusts and droplets, a gas of electrically neutral atoms has effectively zero RCS, but a gas of ions containing separated free charges can be an efficient target in the Mie and optical regions.[6] Such a state is called a plasma, which is still electrically neutral overall but can support induced currents.[7] Plasma RCS is sensitive to the wavelength of the radar and the ion density. Generally, long wavelength radar and a high density of free electrons are conditions for significant RCS.

Free plasmas in nature - such as lightning channels in the lower atmosphere or auroral streamers and meteor trails in the upper atmosphere - are regularly detected by radars, incidentally or by design. In the case of lightning strokes and meteors the fast charge recombination rates mean that they appear only as extremely short-lived point targets usually detected only on a single scan of a surveillance radar. Aurorae are more persistent but present as large, fluctuating, diffuse area targets many degrees of arc in extent. These types of plasma are not generally of interest for the purposes of this study.

The head echoes of large, slow, fireball meteors might behave to certain radars as spheroidal plasmas but will only rarely be detected on several successive scans and thus from the radar user's point of view are likely to be disregarded or electronically suppressed as sporadic noise. More interesting for our purposes are the tropospheric phenomena generally known as "ball lightning" (BL) which according to reports may survive for periods that are long relative to typical radar update rates.

BLs appear to be free-floating plasmas held in spheroidal configuration[8] by containment forces that are not well understood. Because the physics is obscure, the occurrence sporadic and the controversial models not predictive, there have (to the author's knowledge) been no studies of BL on radar. But we can make some general remarks.

A natural plasmoid is expected to have a radially varying ion density (generally proportional to a central field strength varying like $1/r$), as in Fig.3, with an effective radio surface being defined by a transition from what are called overdense to underdense states. This surface can be treated as a perfectly conducting metal shell. (Kleinman *et al.*, 1970)

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[6] This difference is exploited militarily in a stealthed radio antenna called a plasma antenna. This is a radar-transparent tube of gas which, when energised, is heated and ionised, behaving like a conductive metal and radiating radio waves, but which when cold and unused recombines to a neutral gas which cannot be detected by enemy radars.

[7] See paper 2.2 for a corollary discussion. (Ed.)

[8] A spheroid represents a minimum-energy surface and for this reason a spheroid (or sometimes an ellipsoid) is usually the only stable solution in viable electromagnetic BL theories.

A spherical plasmoid is the simplest case. For a given spherical plasmoid the radius at which this critical surface occurs will depend on the wavelength of the illuminating radar. It occurs where a parameter called the plasma frequency, proportional to the charge density, exceeds the electromagnetic frequency of the incident radiation. This means that there is a point at which the RCS of a plasma effectively shrinks to zero area and becomes invisible to radar as the frequency increases. Or, in other words, wherever there is a natural spectrum of ion densities in any plasma target, it will have a larger RCS at long wavelengths, behaving electromagnetically as a perfectly conductive reflecting thin shell in some longwave limit. Conversely, the same plasma region will be increasingly radar absorbent at short wavelengths, approaching a perfectly absorbent thin shell in some shortwave limit.

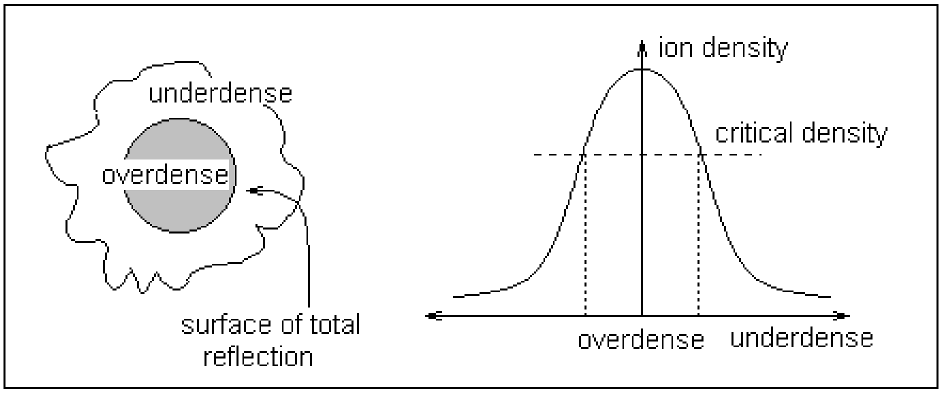

Figure 3. Cross-section through a radially varying electron density around an ionising source. At the critical surface reflection is specular, i.e. the plasma behaves as a radio mirror

So plasmas can be 'tuned' to be either efficient reflectors or efficient absorbers, which gives them a role in possible radar stealth designs and by the same token makes it difficult to predict how plasmoids of unknown structure and cause (natural or not) will behave in a given radar environment.[9]

The possibilities are complicated further by the fact the radar surface of critical reflecting density would not be expected to represent an abrupt transition to a charge density of zero, so if the depth of the outer plasma is significant relative to the radar wavelength then the RCS will be the sum of three processes, absorption, reflection and again absorption.

In addition to this, where the radar frequency exceeds the plasma frequency in the outer layer, the layer can act as a diverging lens. The effect of this lensing is to reduce the apparent RCS of a reflective surface within the layer (Marini,1968). In other cases where an outer plasma layer around a reflective target is itself to some extent reflective (as in the case of a re-entering artificial satellite) the resultant echo signal amplitude will be an unpredictable sum of the phases of the two different reflections, either increasing or

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[9] See section 3 in paper 2.4 regarding radar-emission) for related discussion. (Ed)

decreasing the RCS.[10]

A persistent plasma is by definition in an equilibrium state between an input energy of ion dissociation and an output energy due to ion recombination, and this output is in the form of photons so that a plasma is expected to be generally a continuous optical emitter during its lifetime. It is worth noting that the radar surface - the critical density surface of total reflection - generally need not coincide with the emissive optical surface. Therefore depending on radar wavelength the size of the plasma "seen" by radar may be different from the size of the same plasma seen by the eye or by optical instruments.

Charge polarisation may also be a factor. A secret Defence Intelligence Staff study for UK Ministry of Defence in 2000, codenamed CONDIGN, suggests that dusty plasmas containing charged aerosols may self-organise into a structure that can enhance radar scattering and increase RCS. The strong tendency of the plasmoid to maintain neutral overall charge will cause ions to congregate in oppositely charged clouds which cloak the aerosols, resulting in plasmoids with temporarily-stable multiple cores bound together by electric forces. These cores may then resonate independently under radar illumination, so that the effective RCS of the plasma at changing aspects may be complicated by fluctuations occurring due to cancelling and reinforcing phase effects.

It is presumably possible that such hypothetical plasmas may fragment into multiple independent targets separated by neutral insulating air. In this case the radar signature may be considered that of an aggregate of smaller spherical resonators, the average overall RCS varying unpredictably in relation to the radar wavelength and the dimensions of the radar resolution cell.

8. Conclusions

In the optical or far-field region of Fig.1, where $2\pi r/\lambda \geq \sim 10$, the relative performance of different radars at different bearings from a target will remain (uniquely) constant for a sphere (i.e, RCS is independent of aspect), but near $2\pi r/\lambda \geq \sim 1$ in the Mie region one would expect to find order-of-magnitude differences in target P_d for nearby dissimilar radars due to the resonance effects discussed in Section 3. This means that in a typical ATC radar environment (Section 6) where practical probability of detection P_d of a spherical target in the order of 1m across by radar A at a given range might be (say) 90%,[11] the same primary targer might be detected with $P_d < 10\%$ at the same range by radar B of equal power but different wavelength.

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[10] This effect was first noticed with radar measurements of the re-entering Soviet Sputniks in the early years of the space age. A U.S. study (IEEE, 1963) found that where the echo amplitudes were similar the summation of the two phasors in the simple spherical case could either enhance the RCS significantly or nullify it completely, rendering the sphere invisible to radar.

[11] According to Cole (1985) most users are looking for P_d = 80% - 90% as a desirable efficiency in normal operation. The reason why P_d does not approach 100% may not immediately be obvious from the relatively straightforward radar equation given in Section 1, but is easier to appreciate in terms of the full radar equation given by Cole where the right hand side contains 17 different electromagnetic, propagational and engineering factors, of which the RCS (whose complexity even for the simplest possible target geometry we have begun to appreciate) is but one. To put this in dramatic terms, P_d = 100% is impossible in principle for any real target whatsoever unless its range from the antenna is *exactly* zero.

It is highly likely that natural spherical UAP[12] of this order of size do exist (see Fig.4). There is some indication that artificial[13] spherical aeroforms of this order of size may also exist, or may be in development. Either could potentially impact air safety. Therefore NARCAP should recommend a study of the ability of the traffic control system to respond effectively to possible radar hazards when there is a detection conflict between sensors.

We will now make some further comments on each of these two categories of spheroidal radar target.

i.) Natural plasma spheroids

Another factor possibly prejudicing effective ATC response to natural spheroidal radar hazards of the BL class is their reported short duration. Although this factor is not directly related to the sphericity of the plasmoids, it may have a bearing on the practical impact of other factors that are so related.

The modal duration of BL according to one study (Rayle, 1966) is only 5-7 seconds (25% of cases; see Fig.5) which is comparable to or shorter than typical ATC radar update rates (in the range 5-12 seconds for ASR-9 and ARSR-3 radars), meaning that probability of *tracking* needs to be considered independently of the probability of simple detection above noise level. This difference is often expressed in terms of "thresholds of detection".

A typical tracking filter[14] on a surveillance radar usually operates with a threshold of at least 3 associable plots to avoid overloading the display with spurious track projections interpolated from nearby unrelated targets, clutter and noise (Cole 1985; Skolnik 1981; 1990). One or two data points on a BL may well survive first and second thresholds of

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[12] This would be at the large end of the range of diameters reported for natural lightning balls, given as generally 0.2 - 1.0m (9" - 39") by Stenhoff (1999) but numbers of such estimates do exist. Rayle (1966) found that fully 25% of NASA observers questioned reported diameters in excess of 25" (0.64m) and 10% around 35" or more (~1.0m). On most plausible electrical theories BL plasma size would be expected to be proportional to the stored energy. There is therefore no definite upper limit. Wessel-Berg (2004) calculates that stored BL energy corresponding to a diameter in the order of 10m might rarely be within the range of typical lightning discharge energies, but such estimates are highly theory-dependent.

[13] According to *Avionics Magazine*, Oct 01 2003: "The AINS program [U.S. Office of Naval Research Autonomous Intelligent Networks and Systems project, November 2002] sponsored exercises in August using experimental vehicles such as Silver Fox, a fixed-wing UAV built by Advanced Ceramics Research (ACR), in Tucson, Ariz. . . . [The] UAV has demonstrated the dropping of spherical sensors attached to its wings. These electronically guided, sometimes winged, "eggs" -- with glide slopes ranging from 2-to-1 to 15-to-1 -- have provided video data." http://www.avtoday.com/av/categories/commercial/1126.html

Dr. Jacques Vallée stated in 1993: ". . .there are small spheres about one meter, you know, 3 or 4 feet in diameter, that can hover, they can move in any direction, almost silently or in some cases silently. They are used as ranging devices. . . . Those things have been, you know, technically achievable certainly for the last ten years. These can be used for reconnaissance, they could carry a camera. They're essentially platforms, remotely piloted platforms, that can, that are highly maneuverable." http://www.21stcenturyradio.com/ForbiddenScience.htm

[14] Known as a "track-while-scan" or Automated Detection & Tracking (ADT) system. Note that a local ATC area covered by multiple radars may use an integrated ADIT (Automated Detection and Integrated Tracking) system to compile detections from all radars into a single track file. With a spherical target in the Mie resonance region a counterintuitive situation might possibly arise where the addition of a second radar *reduces* the overall effective signal-to-noise ratio by contributing negative detections and preventing the ADIT filter from assigning a track even on the screen of another radar that has only positive detections.

detection, i.e. the receiver would register a signal above noise level, and the plot-extractor software would present interpulse run-lengths and sample profiles[15] to the display as true detections rather than noise; but the plots would not then be exploitable by the tracking filter, because typically 3 associable surveillance plots will require a *minimum* interval of about 10 seconds. This is a duration equalled or exceeded in only 40% of BL observations according to Rayle (1966), and in this 40% of cases even if the ADT does assign a primary track it will be almost as quickly terminated unless further plots are made on succeeding scans (Skolnik, 1981). Only in about 7% of cases does BL survive long enough to give four successive radar plots.

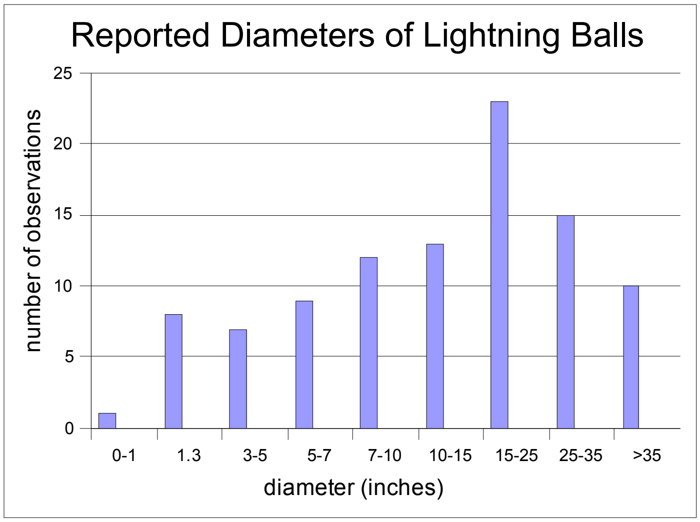

Figure 4. Estimated diameters of lightning balls in 98 observations reported by personnel of NASA Lewis Research Centre (data from Rayle 1966)

Another factor not directly related to the sphericity of targets but of importance with regard to natural BL plasmoids is the range of speeds. In 71 observations by NASA employees tabulated by Rayle (1966) 83% of estimated maximum groundspeeds lie in the range 0 - 60mph. Many such reflectors would be at high risk of being filtered out by Moving Target Indicator settings on ATC radars.

Although spheroidal plasmas have often been observed near and even within aircraft in flight, historically the observations are more numerous near the ground than at high altitude. This may merely reflect witness opportunity (there are obviously more potential observers on or near the ground), but could also be physically significant.[16] If so then it

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15. The 'run length' indexes the number of positive and negative pulse responses during the beam's dwell time on target, and techniques such as the "sliding window" are used to prepare an envelope profile (i.e., signal rise and decay slopes) from the amplitudes of the successive pulse echoes. The envelope is then compared with a library of envelopes typical of aircraft echoes to decide if a "real target" is present.

16. According to several theories it is the conventional cloud-to-ground circuit that maintains the ball, suggesting that BL will form below the charged cloud base, i.e. in the middle to lower troposphere. In Wessel-Berg's "free-space spherical transmission" model (Wessel-Berg, 2003; 2004) spheres are favoured solutions at low level, whilst other geometries would predominate at altitude - a pattern which Wessel-Berg claims matches observation.

would be more likely for aircraft to encounter BL during terminal manouvering than *en route*, i.e. when the BL is at low altitude and at relatively short range from relatively large numbers of radars. From a research point of view this would mean that the distribution of occurrence of spheroidal plasmas may conveniently be positively correlated with the completeness and redundancy of radar cover; but, inconveniently, it would be *inversely* correlated with the amount of attention that will be spared for them by aircrews and Air Traffic Controllers, as long as they are regarded as a low-priority, low-risk issue.

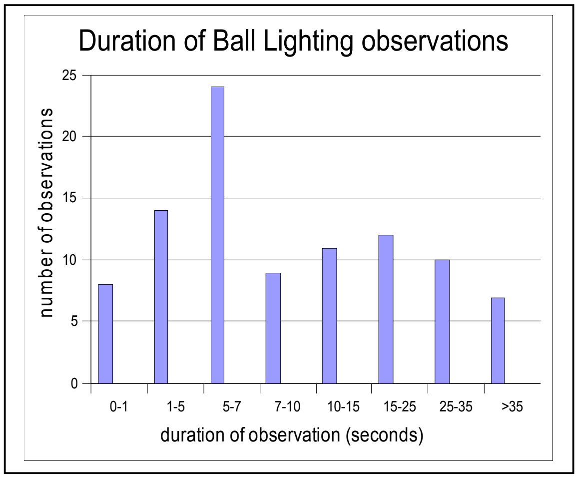

Figure 5. Estimated durations of lightning balls in 96 observations
reported by personnel of NASA Lewis Research Centre
(data from Rayle 1966)

These factors give added point to the air safety considerations: Terminal radar control (TRACON) areas are the most congested airspaces, extending up to perhaps 13,000ft for a few tens of miles around major airports and covered usually by multiple S-band radar heads of the ASR-9 class with outputs centralised at a remote TRACON facility. Here is where the highest level of aircrew and controller workload coincides with the highest level of risk to commercial planes due to their proximity to the ground, to birds, to uncontrolled primary traffic and to one another.

It is therefore of concern, given these psychological and environmental factors, that we have identified several physical and engineering factors that may tend to prejudice the radar P_d of plasma spheroids. These include:

- unpredictable variability of RCS due to plasma absorption and phase interference effects;
- fugitive and possibly conflicting radar responses in the Mie resonance region;
- spherical/elliptical polarisation losses; and
- MTI suppression.[17]

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[17] On the other hand it may conceivably be the case (depending on the unknown physics of BL) that relatively rapid oscillations on a scale of cms, such as internal turbulence, spinning, radial scale fluctations, or oscillatory bulk displacements, might occur which defeat MTI filters by returning phase-shifted echoes even if a plasmoid is on average stationary.

To these factors we can add that because plasma RCS will in general be positively correlated with radar wavelength (Section 7.iii), and because *en route* ATC radars tend to operate with longer wavelengths than shorter-range TMA radars (Table 1),

- the P_d of BL by air traffic surveillance radars will tend to be higher in the upper troposphere (tens of thousands of feet) where its frequency of occurrence is lowest, and lower in just those low-level TMA airspace volumes (thousands of feet and below) where it seems most likely to be encountered.

Moreover, we note that insofar as lightning is regarded as a "weather" phenomenon, BL-type plasmoids may be an under-emphasised air traffic risk if reliance on integrated weather radar products - such as the FAA Integrated Terminal Weather System (ITWS) operational since 1998 - encourages complacency on the part of Controllers. BL plasma spheroids appear to be strongly correlated with thunderstorm conditions, but do not always occur near or during active electrical storms, and whilst ordinary lightning strokes can be monitored by passive RF lightning mappers and other means, and their associated storm cell precipitation detected and predictively mapped by weather radars, BL falls through both the lightning-detector and radar nets. Weather radars such as WSR-88D are short wavelength (Table 1), optimised for precipitation, and unsuitable for detection of echo from plasmas, in addition to which they employ slow volume scan algorithms whose update rates (up to 10 minutes) are useless for obtaining timely data on phenomena whose mean lifetime is measurable in seconds.

ii.) artificial spheroids

Hypothetical artificial aerial spheroids may behave like simple metal reflectors, in which case the considerations of Sections 1 to 7.ii apply. By definition (Section 1.ii) the RCS of a simple spherical conductor must be proportional to its projected area. An exception would be spheroids constructed using traditional Radar Absorbent Materials (RAM) or microwave metamaterials, as mentioned in Section 7.i.

Metamaterials are like a honeycomb or matrix of small radio waveguides whose geometry is carefully calculated to control the behaviour of radio waves incident on the material, potentially in more efficient and controllable ways than traditional RAM coatings An object whose gross geometry, on a scale $>>\lambda$, is that of a simple sphere might be stealthed by a cloak of metamaterials that give it a more complex surface geometry on scales $<\lambda$. Such materials can, in principle, be designed to duct energy around an object, so that, at the particular design wavelength, it has an RCS that is small or zero and so is effectively invisible to the radar even though it may be constructed of an intrinsically radar-reflective conductive material. (Schurig *et al.,* 2006; see also Alù *et al*., 2004; Cui *et al*., 2008)

Given that unidentified spheroidal aeroforms do exist, it is also possible to imagine that the technologies of lift, propulsion or concealment involve the generation of a plasma sheath around the vehicle.[18] The principle has been considered for control of laminar flow around airframes - both for increasing aerodynamic efficiency and for suppressing sonic booms. - and also has applications in radar stealth. (Chow *et al.*, 2002) Experimental

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[18] Clearly a sphere has zero average aerodynamic lift (apart from a possible small Magnus Effect lift if in rapid rotation) and, if it is not neutrally buoyant, relatively exotic flight principles might be implied. It is not our purpose here to speculate about such principles. [Also see Paper 2.1.1 for further relevant information; Ed.]

systems are known to have been tested in various countries including Russia, the US and France. In 2002 a Russian plasma stealth system was reported as being installed in a combat production aircraft, offering a factor 100 reduction in RCS. (Fiszer & Gruszczynski, 2002)

Whilst an overdense plasma surface will act as a radar mirror (Section 7.iii), effectively increasing the target's projected area and therefore its RCS, an underdense sheath is in principle an efficient absorber and instead of reflecting incident microwave energy back to the transmitter will transduce it into heat (and possibly light).[19] Also as mentioned in Section 7.iii divergent lensing would be expected within an underdense spherical plasma, so that the effective residual RCS due to radar energy reaching a vehicle within such an absorbent sheath might be somewhat further reduced.

It is possible that phasor addition of reflections from a solid metallic core and from a partially radar-transparent surrounding plasma sheath might eliminate the resultant RCS entirely (IEEE, 1963). But generally such phase effects will be fortuitous, dependent on unpredictable physical and electromagnetic variables. Useful control of such an effect seems less likely than the use of a plasma sheath as a microwave absorber, although to be fully effective in practice both presuppose impressive systems agility, from sensor to reactive hardware.

Another theoretical possibility for a smart sphere capable of rapid analysis of incident radar wavelength is exploitation of the variable RCS occurring in the Mie resonance region. This would require reactive variable-geometry, specifically change of physical radius. The simplest case would be inflation-deflation of a spherical skin (such as a metallised fabric) by control of gas pressure, which one might imagine being a technique open to the new class of part-buoyant Hybrid Air Vehicles (HAV) being developed by the US and UK for long-endurance surveillance.[20] Far-fetched, perhaps, but small changes of sphere radius near $\lambda = 2\pi r$ could allow a factor-15 control over RCS. This corresponds to a power ratio of only ~12dB, which is small compared to ~30dB or more achieved by proven stealthing techniques (about 1.5%) and claimed for plasma stealth (1%) but might not be negligible in some marginal cases.

Whether any small, smart, spherical devices exploiting Mie resonance mechanically have ever been conceived, designed, or flown is a matter for speculation, but it seems unlikely. Electromagnetic inflation-deflation of the effective radar-echoing area of a plasma sheath by varying the plasma frequency (Section 7.iii) is perhaps a slightly less impractical way to implement this principle, if it were ever thought worthwhile.

In summary, certain limitations on efficient radar detection of both natural plasma spheroids and hypothetical spherical devices have been identified. In terms of NARCAP's

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[19] There may be a trade-off to be considered between reduced RCS and an increased target signature for thermal-optical tracking systems.

[20] E.g., Lockheed Martin's LEMV (Long Endurance Multi-Intelligence Vehicle) and the Skycat developed by HAV Ltd at Cardington in the UK. These helium designs are typically 60-80% buoyant. But they are generally much too large for Mie resonance effects to be relevant and are not spherical. Spherical airships have been marketed in recent years by, among others, Cyber Aerospace Corporation and Techsphere Systems International in the US, but again these are very large, bigger than $10*2\pi r/\lambda$ except for long meter waves and thus well into the linear optical region for practical radar purposes. Presumably classified meter-sized HAV programs for specialised applications may exist as well as these white-world private-venture vehicles.

mission, we raise the concern that such phenomena could, in certain circumstances, pose a potential risk to air safety that may be underestimated in current ATC system design and operation.

9. Recommendations

The general definition of the risk R_o of an event is the product

$$R_o = P_o * I_o \qquad 2$$

where P_o = *probability* of occurrence and I_o = *impact* of occurrence. For example, impact of an asteroid strike (measured on some appropriate scale of damage) would be very high, but probability might be very low, leading to only moderate risk. Similarly, the probability of occurrence within a given radar environment of meter-scale spheroidal flying devices may be deemed small (both *a priori* and because of normal effective airspace zoning) but the potential impact of their occurrence, in circumstances where radar P_d may be degraded (Section 8), has to be assumed to be relatively large. Conversely, the probability of occurrence of natural spheroidal plasmas may be intrinsically quite large[21] yet the impact may be relatively small (no known directly attributable fatalities, and pilot reports of BL manifesting harmlessly near and even inside aircraft, suggest that it can be unexpectedly benign[22]). It is possible that the risk product R_o might be similar in both cases.

No attempt has been made here to quantify this risk, but intuitively it might be thought negligible. After all, code traffic, primary traffic and various types of radar noise and clutter - including natural hazards such as birds - generally co-exist peaceably on-screen, and rare transient phenomena of the type considered here ought not to contribute very significantly against this background. But the range of properties and effects of BL plasmoids remains very uncertain, whilst related atmospheric electrical phenomena continue to be discovered (e.g., sprites, jets etc); and we note that the availability of small UAV-type devices has spread in recent years beyond the traditional aerospace users (government agencies and prime military contractors) and into the hands of small opportunistic entrepreneurs, individual "inventors" and hobbyists,[23] a trend which tends to imply an increasing chance of conflict with controlled air traffic.

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[21] Some estimates suggest it may be commonplace, simply not easily visible in daylight beyond a few tens of meters and thus under-sampled by observers, (Altschuler, 1970) but the true rate is unclear. A rate of $3*10^{-9}$ km^{-2} min^{-1} has been inferred from automated lightning camera photographs, and a figure of 3 percent of the frequency of ordinary cloud-to-ground lightning strokes has been derived from observer reports (Barry, 1980). A NASA map of global lightning frequency (see http://thunder.nsstc.nasa.gov/data/) suggests that these estimates are in order-of-magnitude agreement for a rate of lightning strikes appropriate to low storm incidence areas (such as the U.K., Scandinavia, N. Canada and some ocean areas).

[22] Of course BL could be involved in unsolved fatal air accidents and we would not necessarily know about it. Damage reportedly has occurred.

[23] C.f., the semi-rigid rotating Girostats and other powered "micro-airships" - from 2ft balloons to 36ft dirigibles - flown by amateur rocket builder Frank Sharman in the UK (from about 1989), see: http://www.unrealaircraft.com/wings/girostat.php ; or the powered spherical balloons and blimps of Mikhail Kuzmek in Belgium during the same era, which have been claimed (admittedly on unconvincing evidence) as contributors to the Belgian wave of UFO sightings 1989-93, see e.g. http://adelmon.free.fr/vaguebelge/Kuzmek1.html

Therefore NARCAP should recommend that FAA radar data-collection procedures be audited to ensure that the Administration is in a position to effectively prevent - or to react in a timely and effective fashion to any failure to prevent - future conflicts between UAPs and code traffic in controlled airspace.

In an ideal world, given some of the sensor limitations and potential risks mentioned in Section 8, one would like to recommend that long-wavelength, rapid-update acquisition and target-following radars, tailored for short-lifetime UAP detection and bypassing the limitations imposed by ADT and MTI signal processing filters in traffic control, be deployed to monitor busy low-altitude airspace volumes. Such a dedicated raw radar product could be made optionally available to Controllers in real time alongside precipitation and wind-gust display overlays *via* the integrated ITWS (thus complementing, not compromising, the functionality of the ATC signal processing).

But such a step, however desirable (from the point of view of research as well as of air safety), would rightly be considered costly and impractical by industry and regulators, even if the risk product (see above) were considered not negligible. Any improvement in real-time detection of natural BL plasmoids needs to be acted upon to reduce practical risk, but communication and reaction times are probably longer than the typical plasmoid lifetime, and air safety gains would probably be negligible.

Indirect safety benefits might accrue from non-real-time study of transient UAP detections by existing ATC radar systems. However, mere routine analysis of past radar data logs would not necessarily provide data useful for research. Past experience indicates (e.g. Haines, et.al., 2007) that combing FAA datasets for plots of low- P_d UAPs that may be characterised by small RCS and short lifetime is likely to be inconclusive. This is because primary echo data are typically reduced to digitised plot-extracted form at the radar head (see Section 8.i), permitting rapid dissemination to Control rooms by narrow-bandwidth telecoms channels but permanently dumping non-track-associated target plots and raw pulseform data that could be useful for scientific analysis.

Therefore NARCAP should recommend a study by radar engineers for presentation to FAA on the cost and practicality of automatically saving raw analogue data at the radar head, prior to digital plot-extraction and MTI filtering, for detailed non-real-time analysis. This would place no pressure either on the restricted transmission bandwidth between radar head and controller display or on the controller's real-time vigilance, but would make the primary echo pulseforms of transient UAP phenomena available for scientific research and could provide vital data for ATSB investigations in the event of air accidents related to UAPs.

In summary, in the context of the limited remit of this paper, we draw attention tentatively to the following particular recommendations:

- FAA should investigate the cost of routinely preserving pre-filtered pulseform data on uncorrelated primary echoes for later technical analysis.
- FAA should undertake a study of the ability of the traffic control system to respond effectively to possible meter-scale UAP radar hazards when there is a conflict between nearby sensors operating at different wavelengths (see Section 8.i, Note 12)
- FAA should ensure that Air Traffic Control managers familiarise radar room staff

with the possible radar characteristics of short-duration, sub-meter-scale plasma spheroids - e.g., slow-moving, variable-RCS primary echoes on short tracks

- in furtherance of which, ATC and carriers should maintain up-to-date reviews of:
  a) literature in relevant areas of meteorology, plasmadynamics and plasma stealth technology
  b) information on government and private-venture UAV development programs; and
  c) reliable sources of research in the field of anomalistics

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