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1 **In situ multi-frequency measurements of magnetic susceptibility as an indicator of planetary regolith**
2 **maturity**

3

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26 **Abstract**

27

28 Space weathering is now generally accepted to modify the optical and magnetic properties of airless
29 planetary regoliths such as those on the Moon and Mercury. Under micrometeorite and ion bombardment,
30 ferrous iron in such surfaces is reduced to metallic iron spheres, found in amorphous coatings on almost all
31 exposed regolith grains. The size and number distribution of these particles and their location in the regolith
32 all determine the nature and extent of the optical and magnetic changes. These parameters in turn reflect the
33 formation mechanisms, temperatures, and durations involved in the evolution of the regolith. Studying them
34 in situ is of intrinsic value to understanding the weathering process, and useful for determining the maturity of
35 the regolith and providing supporting data for interpreting remotely sensed mineralogy. Fine-grained metallic
36 iron has a number of properties that make it amenable to magnetic techniques, of which magnetic
37 susceptibility is the simplest and most robust. The magnetic properties of the lunar regolith and laboratory
38 regolith analogues are therefore reviewed and the theoretical basis for the frequency dependence of
39 magnetic susceptibility presented. Proposed here is then an instrument concept using multi-frequency
40 measurements of magnetic susceptibility to confirm the presence of fine grained magnetic material and
41 attempt to infer its quantity and size distribution. Such an instrument would be invaluable on a future mission
42 to an asteroid, the Moon, Mercury or other airless rocky Solar System body.

43

44

45 **Keywords:** magnetic susceptibility, space weathering, planetary regolith, maturity

46

47 1. Overview of space weathering

48 Amongst the first things to be noted on analysis of the Apollo and Luna samples brought to Earth was that
49 regolith samples had quite different magnetic and optical properties from rock samples, even those which
50 were chemically and mineralogically similar (Hapke et al., 1975). It became clear that these differences were
51 due to a surface maturation process operating in the upper few millimetres of the regolith. Various metrics
52 were defined to quantify the amount of time a particular regolith had been exposed in this way (Langevin and
53 Arnold, 1977). These all rely on the cumulative effects of solar wind bombardment, micrometeorite impacts
54 and cosmic rays. Such weathering agents, and their effects on the regolith, are collectively known as space
55 weathering. The most durable of these metrics was the ferromagnetic resonance (FMR) index, defined as
56 I_s/FeO , where I_s is the magnitude of an observed resonance feature and FeO is the weight percentage of iron
57 oxide in the regolith (Morris, 1976).

58

59 This strong absorption feature, measured with an electron spin resonance (ESR) spectrometer, is believed to
60 originate from spherical metallic iron grains of between approximately 4 and 33 nm in diameter (Morris,
61 1976). These same grains are now understood to play a key role in the optical effects of space weathering,
62 which result in the reddening, darkening and a reduction in spectral contrast of visible and near-infrared
63 (VNIR) reflectance spectra. The theory that vapour-deposited coatings might be responsible for the optical
64 and magnetic properties of the regolith was first advanced during the initial analyses of lunar samples
65 (Hapke et al., 1975) but was not verified until modern laboratory techniques were applied (Keller and McKay,
66 1993). Theoretical modelling has also demonstrated that a vapour coating containing spherical metallic iron
67 grains can indeed replicate the optical effects of space weathering (Hapke, 2001). Various terms have been
68 used to describe this iron, in particular sub-microscopic metallic iron (SMFe) and nanophase iron (npFe⁰). As
69 this paper refers mainly to the magnetic properties of nanometre sized iron particles, the latter is perhaps
70 more appropriate here.

71

72 Several missions, including the MESSENGER and BepiColombo missions to Mercury, the Dawn asteroid
73 mission and several lunar orbiters are currently scheduled to perform remote sensing of airless bodies, or
74 more specifically their regoliths. Determining surface mineralogy from such measurements is greatly
75 hindered by space weathering. The spectral alteration can in fact be so severe as to mask completely weak
76 absorption features, making even mineral identification impossible, let alone quantitative comparisons.

77

78 Ideally, all remote sensing measurements would be supported by in situ, ground truth, data. If the same
79 weathering processes that occur on the Moon also play key roles on other airless bodies, ferromagnetic
80 resonance should be a useful measurement on those as well. ESR spectrometers work by applying a
81 magnetic field across a sample, causing unpaired electrons to align their magnetic moments either parallel or
82 anti-parallel to the field. These two states have different energy levels, with a separation determined by the
83 strength of the applied field and the gyromagnetic ratio (the “g-factor”), which is modified from the free
84 electron value by the electronic environment of the nucleus. A transition can be induced between these two
85 states by the absorption of electromagnetic radiation with the same photon energy as their separation. Thus
86 an absorption spectrum can be produced by varying either the frequency of applied radiation or the strength
87 of the magnetic field. The nature of such spectra can reveal much about the environment of the unpaired
88 electrons, which in inorganic materials are typically associated with transition metals. In ferromagnetic
89 materials, such as the metallic iron grains found in the lunar regolith, the resonance feature is orders of
90 magnitude stronger than that seen in a paramagnetic material, due to the coupling of spins. The frequency
91 and field strength at resonance are used to derive the g-factor, which varies from the free electron value of
92 approximately 2.0 according to the electronic structure; most lunar samples measured have values of
93 2.10 ± 0.03 (Manatt et al., 1970).

94
95 Typical laboratory ESR spectrometers are necessarily massive and unwieldy pieces of equipment, using
96 large electromagnets to generate substantial magnetic fields (typically on the order of hundreds of milli-
97 Tesla). A fixed monochromatic source of microwave energy is usually employed and the reduction in
98 received energy monitored as the magnetic field strength is scanned.

99
100 Miniaturised ESR/EPR spectrometers have been proposed for planetary missions (Kim et al., 2004). In such
101 instruments, it is typically the microwave frequency that is scanned whilst the magnetic field strength is held
102 constant. Two configurations were developed by Kim et al. (2004), one requiring sample ingestion and the
103 other a “contact sensor” using a microstrip resonator. Such an instrument has been suggested to search for
104 organic radicals on Mars and to identify radiation damage in minerals (Yen and Kim, 2004). This approach
105 leads to a considerably lower mass and power than laboratory equipment; the field prototype had a mass of
106 only 1.7 kg.

107
108 This reduction in mass is very promising and should be further developed. However, this paper proposes a
109 much more compact instrument concept which uses multi-frequency measurements of magnetic

110 susceptibility to infer the presence of sub-microscopic iron. Theoretically it could have a mass an order of
111 magnitude less than the ESR instrument. Additional data that could be provided by such a sensor include
112 basic magnetic mineralogy and electrical conductivity of the regolith.

113 2. Magnetic properties of extraterrestrial regoliths

114 2.1. The lunar regolith

115 Since most of our understanding of space weathering derives from the Moon, the case of the lunar regolith
116 will be discussed first. Metallic iron in lunar regoliths is thought to derive from several sources: direct
117 meteoritic input (e.g. from metal-bearing meteorites), reduction of hydrogen-rich regolith as a result of
118 micrometeorite impact heating (hydrogen having been implanted from the solar wind) and the production of
119 surface-correlated iron from the re-condensation of vapour produced in solar wind sputtering and
120 micrometeorite impacts. Subsequent gardening of the regolith can result in this iron being re-worked into the
121 regolith, for example becoming bound into agglutinates. One possible way of distinguishing these sources of
122 iron is by their grain size range and their location in the regolith (Morris, 1980), although thermal annealing
123 processes can increase grain sizes over time (Noble and Pieters, 2003) and so this approach is not uniquely
124 diagnostic. Determining the relative contributions of these processes on the Moon is important for
125 understanding their differing contributions throughout the Solar System, which should scale with factors
126 including the heliocentric distance, the size of the body, presence of a magnetic field etc.

127

128 In terrestrial geology, magnetic susceptibility is primarily dominated by iron oxides such as the
129 titanomagnetite series (Carmichael, 1989). Magnetism on Mars is also believed to be dominated by iron
130 oxides and sulfides (Rochette et al., 2005). In the lunar (Fuller and Cisowski, 1987), and by analogy
131 Mercurian or asteroidal, environments such oxidised minerals are not readily formed. Extensive analysis of
132 lunar samples has shown that the main carriers of ferromagnetism on the Moon are metallic iron and iron-
133 nickel grains. As such, magnetic susceptibility (χ) should correlate well with the amount of metallic iron in the
134 regolith. It has in fact been shown for a limited set of samples that χ/FeO correlates extremely well with
135 I_s/FeO and so should make a good maturity index (Oder, 1992). This normalisation to the weight percentage
136 of FeO is required since the amount of metallic iron is related to both the degree of weathering and the
137 amount of iron oxide in the original, unweathered, material.

138

139 Although no such in situ extraterrestrial measurements have been made, low field magnetic susceptibility
140 (that is, magnetic susceptibility measured at a field too low to produce irreversible changes in the sample
141 magnetisation) has been measured in the laboratory for many samples of lunar regolith. The typical range of
142 mass susceptibility for lunar regoliths is around $1400 - 4400 \text{ } 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ (Carmichael, 1989), depending on
143 the mineralogy and maturity of the sample.

144

145 Magnetic susceptibility is, of course, not a unique measurement of iron content. The majority of lunar
146 minerals are paramagnetic and the total susceptibility also reflects their various contributions. However, the
147 cumulative effects of weathering are understood to increase the ferromagnetic metallic iron content in the
148 regolith as it matures. Although the susceptibility of this iron is a complicated function of temperature and
149 grain size, it is always considerably larger than the paramagnetic susceptibility. Thus only a few wt% of
150 metallic iron, as found in a mature lunar soil, can dominate the magnetisation of such a sample.

151

152 Ferromagnetic susceptibility is critically dependent on the magnetic domain state of the magnetic carrier.
153 Large iron grains will be multi-domain (MD), such that neighbouring domains are oriented with opposing
154 magnetic polarities in order to reduce magnetostatic energy. It is relatively easy to change the magnetisation
155 of such a material and hence the coercivity is low. Below a critical size, this energy saving is less than that
156 required to split a single domain into two, and hence the material will remain single domain (SD). In this
157 state, ferromagnetic materials are strongly resistant to magnetic change and hence have a higher coercivity.
158 It is magnetite grains of this type that allow the Earth's geomagnetic signature to be recorded and retained
159 over geological timescales. Even so, any acquired magnetism decays over time in an exponential fashion,
160 described by its relaxation time. As the grain size is decreased further, thermal effects become important. At
161 a critical temperature and size, thermal agitation overcomes the magnetic ordering and the atomic moments
162 of such particles are free to orient with an applied magnetic field. Such particles will behave like
163 paramagnets, but with a vastly greater magnetic moment and magnetic susceptibility, and hence are called
164 superparamagnetic (SPM). Usually, a material is considered SPM if its relaxation time is comparable to or
165 smaller than the measurement time in a typical experiment (i.e. if its decay is observed). The boundary
166 between SD and SPM grains in a given sample is therefore a function of the experiment being performed
167 and the temperature of the sample. Figure 1 shows a plot of the variation of susceptibility of metallic iron
168 grains at room temperature with size, based on Néel theory (Néel, 1949) and following Stephenson (1971a),
169 which demonstrates how SPM particles can have a magnetic susceptibility an order of magnitude larger than
170 SD grains; this figure will be discussed in more detail later.

171

172

[Figure 1]

173

174 Metallic iron with characteristic of all of these size ranges (SPM, SD and MD) has been detected via
175 magnetic measurements of lunar materials, although a large proportion of the Fe^0 in mature regolith is
176 superparamagnetic (Dunlop and Özdemir, 1997). Theoretical studies have shown that the range of sizes and
177 shapes possible for SD metallic iron are rather small, and almost non-existence for spherical grains (Butler
178 and Banerjee, 1975). These authors calculate that only 9% of the metallic iron the lunar regolith need be
179 single domain to reproduce the measured magnetic characteristics. Somewhat oblate spheroid grains, for
180 example with an elongation of only 10%, are sufficient to fulfil this criterion. The FMR signature, however,
181 arises from grains that are single domain and close to spherical (and hence have negligible shape
182 anisotropy). Thus it is likely that metallic iron grains dominated by both magnetocrystalline (spherical) and
183 shape (spheroid) anisotropy are present in the lunar regolith.

184

185 It is, however, the presence of extensive SPM material in lunar regoliths which dominates their magnetic
186 susceptibility. The proportion of SPM grains is, in turn, a function of space weathering. It can be seen that
187 measuring the initial magnetic susceptibility of a sample in situ, coupled with measurements of bulk
188 composition from complementary instrumentation, should give a good first indication of the degree of regolith
189 maturity and hence the degree of spectral alteration that should be expected in, and ideally removed from,
190 remote reflectance spectra.

191

192 Simple but effective models have shown that a given reflectance spectrum of an un-weathered material can
193 be numerically manipulated to simulate weathering by the linear addition of a volume and surface correlated
194 component of metallic iron (Hapke, 2001). In practice, the spectrum is inverted to obtain the single scattering
195 albedo using a simplified radiative transfer model. Once the complex refractive index of the measured
196 sample has been obtained, this is combined with the optical constants of metallic iron and the process
197 reversed. The size of the host grains, the weight percentage of fine grained iron and the distribution between
198 surface and volume correlated iron are all critical parameters in this model.

199

200 Thus in situ measurement of the amount and size distribution of metallic iron could theoretically allow
201 weathered spectra to be inverted to yield the un-weathered properties. Unfortunately this is a non-trivial task
202 even in a terrestrial laboratory. Attempts have been made to measure the size distribution of metallic iron

203 spherules in a small subset of lunar samples by SEM and TEM (James et al., 2003), but this clearly is not
204 useful for in situ investigation.

205 **2.2. Other Solar System regoliths**

206 The discussion of regoliths here applies mainly to airless bodies, where both solar and micrometeorites
207 regularly impinge upon the surface. However, evidence from Martian meteorites also points to a mechanism
208 for impact shock metamorphism of olivine to produce similar nanoparticles, probably during larger impacts
209 and over a larger spatial scale (Van de Moortèle et al., 2007).

210

211 Mercury is also most likely a highly weathered surface, as its location in the inner Solar System results in a
212 high impact flux and greater average impact velocities than at the Moon (Cintala, 1992). However, the
213 intrinsic magnetic field discovered by Mariner 10 and verified recently by Messenger (Anderson et al., 2008)
214 is expected to stand off the solar wind, at least some of the time, limiting the role of solar wind sputtering, at
215 least at certain combinations of latitude, heliocentric distance and solar condition.

216

217 Asteroidal regoliths are also of great interest, and here it should be noted that the presence of a magnetic
218 field can also play a role, again preventing access to the surface of a body. In the asteroid belt, where solar
219 wind sputtering might be expected to dominate over impacts, weathering could potentially be inhibited
220 (Vernazza et al., 2006).

221

222 **2.3. Laboratory regolith analogues**

223 The motivation for this paper derived from laboratory experiments performed to simulate the space
224 weathering process, with particular reference to Mercury. In these experiments (Bentley, 2004; Bentley et al.,
225 in preparation), powdered olivine samples were irradiated under vacuum with a pulsed IR laser to simulate
226 the weathering process. As with previous experiments (e.g. Sasaki et al., 2001) this resulted in optical
227 changes resembling those seen to have occurred in lunar samples. A variety of magnetic techniques was
228 then used to characterise the changes, including ESR spectroscopy, vibrating sample magnetometry and
229 multi-frequency measurement of the magnetic susceptibility.

230

231 In these latter experiments (Bentley et al., in preparation), a Bartington MS2-B sensor was used to record the
232 magnetic susceptibility before and after irradiation. This instrument uses an AC technique with a field

233 strength of approximately 250 μT (peak) and measurement frequencies of 0.465 kHz and 4.65 kHz. These
234 frequencies are sufficiently low that any conductive losses should be minimal. Samples of San Carlos olivine,
235 sieved to $< 63 \mu\text{m}$ and each with a mass of 2 g, were measured using the Bartington device before and after
236 irradiation. The total bulk magnetic susceptibility of the samples typically increased several-fold after
237 irradiation, as might be expected if paramagnetic ferrous iron is being reduced to metallic iron. Additional
238 evidence from ESR spectroscopy and other magnetic methods support the hypothesis that metallic iron,
239 some of it superparamagnetic, is produced.

240

241 The increase in bulk susceptibility can be used to make a first, coarse, estimate of the amount of metallic iron
242 that could cause such a change. As an example, one such experiment showed an increase in mass specific
243 magnetic susceptibility after irradiation of $8.79 \pm 0.09 \times 10^{-8} \text{ m}^3 \text{ kg}^{-1}$. If it is assumed that the increase derives
244 solely from the production of multi-domain metallic iron, which has a room temperature initial susceptibility of
245 $3.77 \times 10^{-4} \text{ m}^3 \text{ kg}^{-1}$ (Stephenson, 1971b), this corresponds to only 0.023 wt%, or substantially less if a
246 sizeable fraction is superparamagnetic, and hence has a susceptibility up to 66 times higher (Stephenson,
247 1971a)! Clearly this technique is highly sensitive to the changes attributed to space weathering, which can
248 produce several wt% metallic iron in mature lunar regolith.

249

250 The Bartington device also allowed investigation of the frequency dependent nature of the sample. The un-
251 irradiated samples showed an identical susceptibility at both frequencies, within experimental errors. The
252 same samples after irradiation, however, showed a coefficient of frequency dependence (CFD) of over 4%.
253 Typically a CFD of less than two percent is measured if the material contains no SPM grains, a value in the
254 range 10 – 14% is found for a sample containing virtually all SPM grains and a value in the middle has a
255 mixture of SPM and coarser grains (Dearing, 1999). This frequency dependence arises as a result of the two
256 measurement frequencies corresponding to two different observation times, each of which defines a different
257 SD/SPM threshold; the theoretical explanation for this behaviour will be discussed later.

258

259 There is hence a clear rationale for making in situ measurements of magnetic susceptibility; it can provide an
260 estimate of the metallic iron content and detect the presence of SPM particles. The following section
261 describes how such a sensor might be developed for making a contact measurement on a planetary lander,
262 rover or penetrator and discusses the major hurdles and the operational and calibration difficulties arising.

263 3. **An *in situ* magnetic susceptibility instrument for planetary regolith maturity determination**

264 3.1. **Methods of measuring magnetic susceptibility**

265 Methods of measuring magnetic susceptibility can be divided into two categories. The first measures the
266 force experienced by a sample placed in a magnetic field gradient. In the laboratory, the Evans and Faraday
267 balances are examples of this type. The second uses electromagnetic induction. In the simplest setup, an
268 alternating current is applied through a coil. The sample to be measured is placed inside, or close to, the coil.
269 Magnetic susceptibility is directly related to magnetic permeability [$\mu = \mu_0(1 + \chi)$], which in turn is related to
270 the inductance of a coil immersed in a medium. The required measurement is therefore one of inductance,
271 which can be performed quite simply by a variety of electrical circuits. Typically, AC bridges are used to
272 measure an unknown inductance, in which the resistive and reactive components of the inductance must be
273 separately balanced (Collinson, 1983). In this configuration, when the bridge is unbalanced by the presence
274 of a sample, either the off-balance current can be read, or the bridge can be balanced again to give a zero-
275 current at the null detector. It should again be pointed out that both the real and imaginary parts of the
276 complex magnetic susceptibility are of interest here, and thus these should both be measured. Hence some
277 phase discrimination, or lock-in amplifier is needed to record both the signal in phase with the driving
278 alternating field and that in quadrature ($\pi/2$ out of phase).

279

280 For a single coil configuration, the self inductance change due to the magnetic susceptibility of surrounding
281 material is purely reactive, resulting in a change in the quadrature component of the coil impedance. In
282 reality it is likely that the surrounding medium has a non-zero electrical conductivity. Induced currents flowing
283 through the medium also modify the effective resistance of the coil and this must be accounted for. In such a
284 configuration, the inductance change is usually measured by observing the change of frequency of an LCR
285 circuit in which the inductor is coupled to the sample material.

286 3.2. **The benefit of multi-frequency AC measurements**

287 The measurement of initial magnetic susceptibility at a single frequency can be very useful; the Apollo
288 sample collection has been extensively characterised in this way, and more recently it has been used to
289 classify stony meteorites (Rochette et al., 2008) – a technique that has also been proposed for *in situ* use
290 (Rochette et al., 2004). The additional benefits gained from performing the measurement at several oscillator
291 frequencies are discussed here.

292

293 The utility of multi frequency measurements can be explained with reference to the work of Néel (1949), who
 294 showed that the relaxation time (τ) for a collection of uniformly magnetised (i.e. SD), non-interacting uniaxial
 295 grains is related to the volume (v), temperature (T), saturation magnetisation (j_s) and microscopic coercivity
 296 (h_c) of these grains, by equation 1, where k is the Boltzmann constant and f_0 is a constant, approximately
 297 10^9 s^{-1} for iron.

298

$$299 \quad \tau = \frac{1}{f_0} \exp\left(\frac{vh_c j_s}{2kT}\right) \quad \text{Equation 1}$$

300

301 The coercivity depends on the dominant anisotropy in the material, which in metallic iron is either
 302 magnetocrystalline (spherical grains) or shape (non-spherical grains), and using an AC technique the
 303 measurement time can be taken as the inverse of the frequency. A spherical iron grain has a microscopic
 304 coercivity dominated by magnetocrystalline anisotropy, given by $h_c = 2K_1 / j_s$, where K_1 is the uniaxial
 305 anisotropy constant. A value of $4.8 \times 10^4 \text{ J m}^{-3}$ will be used here (Dunlop and Özdemir, 1997), although
 306 considerably higher values have been reported for iron nanoparticles (Lacroix et al., 2008).

307

308 Knowing these parameters, it is possible to calculate the grain volume (the critical volume) at the boundary
 309 between stable single-domain (SD) and superparamagnetic (SPM) grains, and hence the critical grain
 310 diameter. For example, in a 1 kHz measurement of a collection of spherical metallic iron grains, this
 311 boundary occurs at a diameter 20.3 nm. In other words, grains smaller than this are SPM, whilst those larger
 312 are SD. This is of course only strictly applicable for a material comprising SD grains of a single size. In reality
 313 a range of grain sizes is likely to be present, resulting in a spectrum of decay times, blocking temperatures
 314 and volumes. In addition, the saturation magnetisation depends on temperature, although can be considered
 315 constant well below the Curie point (Stephenson, 1971a), and the coercivity depends on both grain size and
 316 temperature. Nevertheless these approximations are sufficient to explain the fundamental behaviour of fine
 317 particle magnetism with respect to frequency.

318

319 With re-arrangements of Equation 1, it can be seen that the critical volume is proportional to the logarithm of
 320 the measurement time, and so increasing the frequency (decreasing the measurement time) moves the
 321 boundary to smaller grain sizes. As a result, a material with a significant amount of very fine-grained
 322 ferromagnetic material will experience a decrease in total magnetic susceptibility with increasing frequency,
 323 as proportionally more grains become SD. As an example, the Bartington magnetic susceptibility instrument

324 referred to earlier uses measurement frequencies of 0.465 kHz and 4.65 kHz, corresponding to transition
325 grain diameters of 20.7 nm and 19.5 nm, respectively. Thus a decrease in the measured susceptibility
326 between these two frequencies can be explained by the presence of spherical iron grains in this grain size
327 range. This can be readily observed in Figure 1 by imagining a grain with diameter 21 nm, for example. In an
328 AC measurement at 1000 Hz this grain is single domain, however at 100 Hz this same grain is SPM and has
329 a magnetic susceptibility 14.5 times larger.

330

331 Thus direct measurements of magnetic susceptibility with frequency can be used to make inferences about
332 the size distribution of magnetic carriers, however the logarithmic nature of the frequency dependence
333 results in a rather limited iron particle size range. Figure 2 demonstrates this on a plot of SPM/SD transition
334 diameter for metallic iron at room temperature as a function of frequency. It still, however, provides a
335 mechanism for performing a limited degree of magnetic granulometry and at the least is a useful indicator of
336 the presence of superparamagnetic materials. Such a dual frequency measurement, if it had been carried
337 out on the NEAR spacecraft, could have provided additional vital evidence about the nature of space
338 weathering on asteroids.

339

340 [Figure 2]

341

342 Since the blocking volume also depends on temperature, knowledge of the regolith temperature would also
343 be required. If deployed as part of an instrumented sensor package such as the proposed HP³ mole concept
344 (Spohn et al., 2001), such high precision temperature measurements would already be included.

345 **3.3. Complementarity to other measurements**

346 It is worth considering what instrument package might be deployed in a future mission, and hence what
347 synergy can be drawn from flying a magnetic susceptibility instrument alongside more traditional instruments.
348 This section therefore discusses typical in situ instruments that make complementary measurements, and
349 how these measurements might be related.

350 **3.3.1. Mössbauer**

351 The most obvious complementary measurement is that of Mössbauer spectroscopy, which is specifically
352 tailored to the study of iron and iron bearing materials. In nano-scale materials, such as superparamagnetic
353 iron, the magnetic ordering of larger particles is not present. As such, the magnetisation in the absence of an

354 applied field orients randomly, leading to a net zero hyperfine magnetic field. The signature for SPM iron is
355 therefore a singlet situated at zero velocity, while larger iron grains appear as a distinctive sextet.

356

357 As seen previously, the determination of whether a particle is SD or SPM is made by both the sample
358 temperature and the so-called “observation time”. In the case of a Mössbauer measurement, this time
359 corresponds to the duration of a Larmor precession of the ^{57}Fe nucleus and is of order 10^{-8} s. For spherical
360 metallic iron room temperature this results in a blocking diameter of approximately 11 nm. As a result, much
361 of the iron seen as SPM with typical AC susceptibility measurements will be SD in a Mössbauer
362 measurement.

363

364 Measurements of lunar samples have shown that both SD and SPM iron can be detected with Mössbauer
365 spectroscopy (e.g. Morris et al., 1998). The remaining question is whether an in situ instrument would have
366 sufficient sensitivity to detect such metallic iron. For example the lunar regolith contains on average
367 approximately 0.5 wt% metallic iron, with 0.20 ± 0.10 wt% in the size range 0.4 – 30 nm (Morris et al., 1998)
368 The MIMOS II instrument operating on the Mars Exploration Rover (MER) vehicles is capable of detecting
369 magnetite and hematite at the 1-2% level (Klingelhöfer et al., 2003). Newer generations of the instrument
370 (e.g. MIMOS-IIa) are expected to show a significant improvement in sensitivity, however, thus making space-
371 borne Mössbauer and multi-frequency magnetic susceptibility measurements complementary (i.e. probing
372 different SD/SPM thresholds).

373 **3.3.2. Near-IR**

374 Visible and near-IR reflectance spectroscopy are powerful tools to determine mineralogy remotely, typically
375 from orbit. However, it is becoming more common for landed elements to also carry such an instrument,
376 integrated, for example, into a microscope for close-up analysis. Comparison of the spectral properties of
377 rocks and regolith on a small scale with their magnetic properties would be a useful combination to confirm
378 the local effects of space weathering. These data could then be extrapolated to gain an understanding of
379 global weathering properties from orbital remote sensing data.

380 **3.3.3. XRS**

381 X-ray spectroscopy (XRS) of asteroid 433 Eros has been used to argue in favour of a space weathered
382 surface, showing that the minor element ratios correspond well with those of ordinary chondrites (Foley et al.,
383 2006) and suggesting that this supports space weathering as the agent of sulphur depletion, rather than

384 partial melting. Space weathering preferentially removes the volatile components of the regolith, whilst
385 leaving the abundances of rock forming minerals unchanged. Melting would, on the other hand, also change
386 the ratios of other elements. Such indirect evidence for space weathering can therefore be measured with
387 such techniques. However, the primary space weathering process (responsible for the major optical and
388 magnetic effects) is a change of oxidation state, and the formation of metallic iron. This is more directly
389 addressed by magnetic or Mössbauer measurements. Thus magnetic susceptibility and XRS are excellent
390 complementary measurements for studying weathering and potential elemental depletion processes.

391 **3.4. Instrument design and development**

392 Although no magnetic susceptibility sensor has yet been successfully deployed on a planetary surface, there
393 is a rich history of proposed instruments and scientific rationales. In the pre-Apollo era, magnetic
394 susceptibility was proposed as part of a surface and downhole instrument suite designed for characterising
395 the lunar surface (Texaco, Inc., 1961). This suite was developed to breadboard level, but was of a similar
396 size to terrestrial equipment.

397

398 Magnetic susceptibility instrumentation was then proposed as a future surface instrument after initial analysis
399 of the lunar samples (Housley, 1977). Recent measurements of the terrestrial meteorite collection (Rochette
400 et al., 2003 and 2008) have suggested the use of such a sensor on future asteroid (Rochette et al., 2004)
401 and Mars (Rochette et al., 2006) missions. Finally, with attention turning to a human return to the Moon,
402 magnetic susceptibility has been again proposed for identifying useful in situ resources; in fact the SPM
403 metallic iron particles that are the key to space weathering could also allow the production of lunar “bricks”
404 due to their absorption of microwave energy (Taylor and Meek, 2005).

405

406 A magnetic susceptibility instrument has been launched once previously, on the Phobos 2 mission. Carried
407 onboard the PROP-F “hopping” lander (Kemurdzhian et al., 1988), it was a contact sensor using an AC
408 bridge technique designed to make measurements of the magnetic susceptibility of Phobos at each hop
409 (Dolginov et al., 1989). Unfortunately contact was lost with the orbiter before PROP-F was due to be
410 deployed, so no measurements were made.

411

412 The utility of making multi-frequency magnetic susceptibility measurements should now be clear. However,
413 to describe a credible instrument concept, a set of top-level science and instrument requirements must be
414 defined. The range of expected values for bulk initial magnetic susceptibility must be chosen for the target

415 mineralogy; in lieu of detailed knowledge, one can baseline a range sufficient to cover typical lunar regolith
416 samples ($1400 - 4400 \text{ } 10^{-8} \text{ m}^3 \text{ kg}^{-1}$ (Carmichael, 1989)). With laboratory instruments, a decade of frequency
417 difference is typically enough to establish the presence of SPM material, but this naturally depends on the
418 measurement accuracy of a field device. Extending this range will help, but will also enhance the ability of
419 such an instrument to perform magnetic granulometry. As noted, however, higher frequencies result in
420 additional energy dissipation in conductive samples due to the generation of eddy currents, but this can in
421 itself be useful for measuring electrical conductivity, if proper care is taken.

422

423 Of course this measurement cannot be made remotely and requires the sensor to be close to the regolith,
424 ensuring flux linkage with the material being measured. Several deployment mechanisms can be considered
425 for different mission profiles. As with all such sensors, mobility (horizontal or vertical) adds greatly to the
426 utility of the data and a magnetic susceptibility sensor could be deployed on a rover or even a sub-surface
427 penetrating mole. If deployed on a long-range rover, the opportunity is presented for recording maturity data
428 at several locations, for comparison with orbital data. This is vital for bodies other than the Moon where we
429 do not have the laboratory data to calibrate remote sensing techniques for separating compositional and
430 maturity variations, as has been performed for the Moon (Lucey et al., 2000). Alternatively, a mole-borne
431 sensor would be extremely useful for obtaining depth profiles and examining the stratigraphy of a single
432 location. Regolith cores extracted on the Moon show that there is a complex intermixing of layers of different
433 maturities at any given location, with a general trend towards decreasing maturity with depth (Basu and
434 McKay, 1995). Such a sensor would be able to examine this in situ for other bodies. In addition there is some
435 evidence for shock-produced fine-grained iron, which might be expected in a given layer with some lateral
436 extent, following a large impact (Cisowski et al., 1973). Layers of differing maturity could also be accounted
437 for by the creation of a palaeoregolith, in which layers of regolith with a given maturity are “sandwiched”
438 between lava flows of low susceptibility (Crawford et al., 2007).

439

440 Low mass and power magnetic susceptibility instruments already exist commercially for terrestrial
441 applications, and have a suitable range and resolution for the measurements described here. Of course
442 these are not space qualified and substantial re-development would be required before flight. Some of the
443 potential issues that would arise are discussed here.

444

445 3.4.1. Coil geometry

446 Of fundamental importance to any magnetic susceptibility instrument is the design of the coils. A choice of a
447 single coil (operating by self inductance) or multiple coils (mutual inductance) must first be made. There are
448 several advantages to a multi-coil design. Temperature variations affect both coils equally and so
449 temperature drifts are minimised. In addition, the geometry of the magnetic field can be optimised to focus
450 the region of investigation, resulting in finer spatial resolution, important for investigating layered structures in
451 a regolith, for example. The volume of material probed also depends on the spacing of the coils. Finally,
452 compensating coils can be used to minimise direct coupling between the transmitter and receiver. Once this
453 decision has been made, the coil geometry must be optimised for the configuration and application. The aim
454 is to ensure maximum flux linkage with the medium in question; however additional constraints such as the
455 available volume and geometry must be taken into account.

456

457 Several coil geometries could be considered, in particular a planar configuration in which the transmitter and
458 receiver coils are arranged for a contact measurement, for example in the foot of a lander, rover wheel
459 (measuring once per revolution, and allowing a free-space calibration in between) or at the end of a robotic
460 arm. Alternatively a 3-coil linear arrangement, which could be included in an instrumented mole, can be
461 considered. The central coil can either be a transmitter or receiver, with a matched pair playing the opposite
462 role. However, other configurations could be considered, for example incorporating the coils into tracks on a
463 flexible substrate mounted on the inner wall of the mole and avoiding the difficulty of passing signal-carrying
464 wires through the coil.

465 3.4.2. Calibration

466 Since measurement of susceptibility using an AC bridge is a relative technique, some method of calibration
467 is required before each measurement. On the Earth this is performed by making a measurement away from
468 any magnetic material, essentially giving a "zero". In the confines of a lander, and in particular during the
469 penetration of a subsurface mole, this may be impractical.

470

471 Aside from zeroing in free space, the only realistic option that does not involve deployment booms, arms or
472 other mechanisms, is to measure a known material when in close proximity to the sensor. If deployed in a
473 mole, the hammering mechanism could offer a ready solution to this problem by manufacturing the
474 mechanism from a magnetic alloy with stable properties. During each cycle a zeroing measurement could be
475 made when the hammer was close to the sensor. However, a suitable material must be found that has

476 properties that do not change over time, with temperature, and with the energising frequency etc.
477 Alternatively a single-point calibration can be performed by incorporating a calibration material into the
478 housing of the instrument deployment mechanism.

479

480 A secondary issue is calibration of the volume over which the sensor integrates. Measurements of volume
481 susceptibility rely on the sample filling the volume over which the sensor is sensitive. Even so, density
482 changes in a material can be mistakenly recorded as a difference in magnetic susceptibility. For this reason
483 laboratory measurements are often made using mass specific susceptibility, which is normalised by the
484 sample mass (and hence density). Since in situ measurements cannot easily determine the sample mass,
485 additional steps must be taken to ensure consistent values.

486

487 Gattacceca et al. (2004) have shown a method for determining the integration volume of an AC magnetic
488 susceptibility sensor based on measurements alone. This relies on taking measurements at different
489 distances from the sample, such that a different fraction of the integration volume is filled (and recorded) at
490 each distance. This method is suitable for deployment on a rover or robotic arm, but not on a mole. In this
491 case measurement of the bulk density surrounding the instrument could be used to ensure inter-
492 comparability between measurements. Such a sensor, using gamma backscatter densitometry, has already
493 been proposed and built to a breadboard level in a prototype of the HP³ mole-borne instrument package
494 (Ambrosi et al., 2006; Spohn et al., 2001).

495

496 A final point to note is that such a sensor would be rather sensitive to the presence of metal in the instrument
497 housing, or indeed the host spacecraft itself. This can already be seen from laboratory measurements where
498 care has to be taken over the location of the instrument; conductive losses reduce the measured magnetic
499 susceptibility. There are therefore some additional restrictions placed on where and how a magnetic
500 susceptibility sensor can be mounted.

501 **3.4.3. Thermal and mechanical stability**

502 The value of inductance of a coil is strongly affected by the mechanical stability of the coil windings. Careful
503 choice of the (electrically insulating) former would have to be made to ensure a consistent inductance over
504 the expected temperature range. Continuous measurement of temperature and also “blank” measurements
505 of a calibration material before and after measurement of the actual sample can both be used to remove this
506 drift from the measured value.

507

508 While temperature stability of the coil is vital, additional science is possible if the sample temperature can be
509 varied, either actively within the instrument, or passively during, for example, a diurnal cycle. An ideal
510 instrument design would allow the sample to be heated whilst insulating the coil itself from such changes,
511 maintaining the stable oscillator frequency. This is discussed further in section 3.5.

512 **3.4.4. Choice of frequency**

513 One of the critical parameters in making an AC susceptibility measurement is the frequency at which the
514 oscillator is energised. In typical magnetic susceptibility meters, a low frequency is used to prevent
515 conductive losses in the sample medium. However, this must be traded against the desire to increase the
516 frequency range (and hence the iron particle size range) available for magnetic granulometry of
517 superparamagnetic grains.

518 **3.5. Additional science**

519 Not only can such a sensor measure the bulk magnetic susceptibility and search for the superparamagnetic
520 iron indicative of space weathering, but it can also potentially measure electrical conductivity and magnetic
521 mineralogy. When recording magnetic susceptibility in a two-coil (transmitter and receiver) configuration, the
522 response of the coil is measured in phase with the driving current, but the quadrature component is also
523 useful, providing a measure of electrical conductivity. Indeed this technique is often used in terrestrial
524 borehole logging. The internal magnetic field generated by the movement of domain walls and the rotation of
525 domain magnetic moments corresponds to the magnetic susceptibility of the sample and this results in the
526 in-phase signal. The quadrature component represents losses in the sample, from both magnetic hysteresis
527 and eddy currents. Thus the magnetic susceptibility is written as a complex quantity when frequency is
528 considered. As well as being of intrinsic scientific interest, electrical conductivity is of particular interest at the
529 surface of Mercury, where it has been suggested that surface conductivity may play a role in the closure of
530 field aligned currents believed to be generated during magnetic substorms, first detected by Mariner 10
531 (Janhunen and Kallio, 2004).

532

533 Another common technique in terrestrial geomagnetic laboratories is thermomagnetic analysis, whereby the
534 magnetic susceptibility is recorded as a function of temperature. Ferromagnetic materials will show a sudden
535 drop in susceptibility at their Curie temperature. Hence measurements of a particular regolith sample over a
536 range of temperature could aid in the identification of magnetic phases, as previously suggested by Rochette

537 et al. (2004). These temperature changes could either be natural, such as those due to diurnal oscillations,
538 or as a result of active heating. Building a coil around, for example, the oven of another instrument might be
539 a way of making magnetic measurements over a range of temperatures. In addition, Equation 1
540 demonstrated that temperature also controls the critical grain size, and thus heating a sample shifts the
541 superparamagnetic boundary to larger particle sizes, allowing a small degree of granulometry as seen in
542 Figure 3. Again, the dependence is weak, but nonetheless useful. In terrestrial laboratories samples
543 measured in this way inevitably partially oxidise, however much care is taken, but the vacuum environment
544 of an airless planetary body is ideal for such measurements. It has also been shown that the shape of the
545 thermomagnetic curve far below the Curie point is also diagnostic of the size distribution of a single domain
546 ensemble (Stephenson, 1971a).

547

548

[Figure 3]

549 **4. Conclusions**

550 Micrometeorite impacts and solar wind sputtering are now understood to produce nanophase metallic iron
551 from ferrous iron in airless planetary regoliths during the regolith maturation / space weathering process.
552 Metallic iron is ferromagnetic and hence amenable to a wide range of magnetic techniques.

553

554 Magnetic susceptibility is known to correlate well with the more frequently used ferromagnetic resonance
555 index used to describe regolith maturity and thus is a useful parameter for understanding the regolith
556 evolution at a given location. In addition, multi-frequency measurements of susceptibility can be used to
557 identify the very fine grained SPM iron particles resulting from space weathering. Definitive confirmation of
558 space weathering as the agent of spectral alteration on asteroids and other planetary surfaces besides the
559 Moon would be extremely useful.

560

561 Laboratory weathered regolith analogues have confirmed both an increase in initial susceptibility and the
562 introduction of a frequency dependence, along with lunar-like spectral alteration, for even low degrees of
563 alteration. Thus a multi-frequency magnetic susceptibility sensor has been proposed as a means of
564 identifying and potentially quantifying the effects of space weathering in a planetary regolith surface. Direct
565 granulometry with this technique has a rather limited range, but coupled with temperature dependent
566 measurements and complementary instrumentation inferences could nonetheless be made. Such data could

567 eventually be used with models of the spectral alteration process to remove some of the changes caused by
568 space weathering from remote spectra.

569

570 This measurement could be carried out most easily by an AC method in which the change in inductance of a
571 coil placed close to a sample provides a measure of magnetic susceptibility. Terrestrial instruments with low
572 mass and power exist, but the challenges in developing a space-borne instrument are not trivial. In
573 particular, the thermal stability of the instrument is key to achieving a high precision measurement.

574 Deployment as part of a mole-borne instrument suite including temperature and density measurements
575 would be extremely complementary, but the required high level of miniaturisation and integration and risk of
576 potential interference suggest that a surface contact instrument may be more feasible.

577

578 Additional properties that could be measured with such an instrument include mineralogy (through Curie
579 point identification if the sample temperature can be varied), and electrical conductivity. Measurements of the
580 susceptibility with temperature can also help to further constrain the metallic iron grain size distribution.

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584

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750 **Figure captions**

751

752 Figure 1. Theoretical calculation of the size dependence of volume magnetic susceptibility of spherical
753 metallic iron at room temperature. Several different AC measurement frequencies are shown, and the
754 susceptibility is scaled relative to that of SD grains for comparison. It can be seen that SPM grains can have
755 a susceptibility an order of magnitude higher than SD grains, and that the SPM/SD boundary shifts to smaller
756 grains as the measurement frequency increases.

757

758 Figure 2. The SD/SPM boundary for metallic iron grains at room temperature as a function of frequency, on a
759 logarithmic scale. It is clear that the nature of the dependence allows only a small degree of granulometry to
760 be performed. Realistically, measurements would likely only be performed at low frequencies where
761 dissipative effects can be avoided.

762

763 Figure 3. The SPM/SD boundary changes with temperature as well as frequency, although again the
764 dependence is relatively weak. In reality the curve is more complex since other parameters, for example the
765 saturation magnetisation, are temperature dependent.





