

1 Point Discharge Current Measurements beneath
2 Dust Devils

3 Ralph D. Lorenz*

4 Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road,
5 Laurel, MD 20723, USA.

6 Lynn D. V. Neakrase

7 Department of Astronomy, New Mexico State University, Las Cruces, NM, USA

8 John P. Anderson

9 Jornada Experimental Range Headquarters, New Mexico State University, Las
10 Cruces, NM, USA

11 R. Giles Harrison, Keri A. Nicoll

12 Department of Meteorology, University of Reading, UK

13

14 *Corresponding Author. Tel. +1 443 778 2903 Fax. +1 443 778 8939 Email: Ralph.lorenz@jhuapl.edu

15 Submitted to Journal of Atmospheric and Solar-Terrestrial Physics, August 5, 2016

16 Assigned MS ATP-S-16-00311. Revised Version, October 26, 2016

17

18 Abstract

19 We document for the first time observations of point discharge currents under dust devils using a novel
20 compact sensor deployed in summer 2016 at the USDA-ARS Jornada Experimental Range in New
21 Mexico, USA. A consistent signature is noted in about a dozen events seen over 40 days, with a positive
22 current ramping up towards closest approach, switching to a decaying negative current as the devil
23 recedes. The currents, induced on a small wire about 10cm above the ground, correlate with dust devil
24 intensity (pressure drop) and dust loading, and reached several hundred picoAmps.

25

26 Keywords : Dust Devils ; Meteorology ; Atmospheric Electricity

27

28

29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55

1. Introduction

Dust devils are an important agent of dust-raising on Earth and Mars (Balme and Greeley, 2006). On Mars, they are among the most prominent meteorological features, whereas on Earth they are mostly a curiosity but sometimes cause damage or, very occasionally, fatalities (Lorenz et al., 2016). Triboelectric processes typically lead to charging of the lofted dust (Harrison et al., 2016), and even from the earliest days of systematic studies of dust devils, their electrical properties have been of interest. A notable example in the early work is that of Colonel Baddeley of the British Army, who in the 1860s, carried a gold-leaf electroscope into dust devils in India (e.g. Baddeley, 1860; Lorenz et al., 2016).

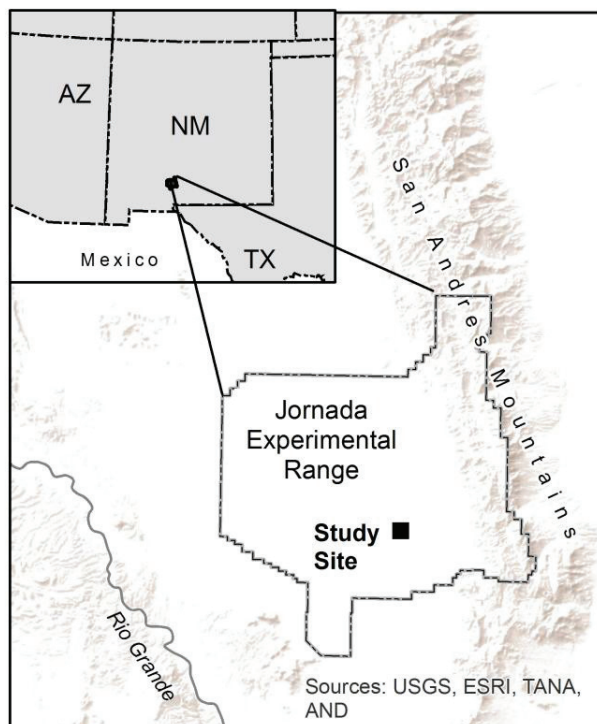
Interest in the electrical properties of dust devils at Mars has been stimulated by the notion that tribochemistry and/or electrical discharges may influence atmospheric chemistry, via the production of oxidants which may play a role in the destruction of organics and/or methane (e.g. Atreya et al., 2006; Delory et al., 2006; Kok and Renno, 2009). In fact early investigators such as Baddeley and others also studied the presence of ozone in terrestrial dust devils (Lorenz et al., 2016), hence understanding the electrical and chemical aspects of dust devils can be appreciated as of enduring importance. The recently-launched European Space Agency (ESA) ExoMars Schiaparelli lander brings new interest in dust devil electrification, in that its DREAMS meteorology package (Dust Characterisation, Risk Assessment, and Environment Analyser on the Martian Surface, Esposito et al., 2014) includes an electric field sensor, with the prospect of providing Mars data to compare with conceptual (e.g. Farrell et al., 2003) and numerical (e.g. Barth et al., 2016) models.

56

57

58 2. Site and Instrumentation

59 Observations were made between 4 May and 14 June 2016 at the Jornada Experimental Range (783
60 km²), 37 km north of Las Cruces, NM. This US Department of Agriculture facility on the Jornada del
61 Muerto Plain lies between the Rio Grande floodplain (elevation 1,186 m) on the west and the crest of
62 the San Andres Mountains (2,833 m) on the east. Just beyond the San Andres Mountains are the dunes
63 of White Sands National Monument, and the nearby missile range, which was the site of a previous
64 visual dust devil survey (Snow and McLelland, 1990). In fact, the Jornada del Muerto itself was the site
65 of measurements of dust devil electric fields made a half century ago (Crozier, 1970).

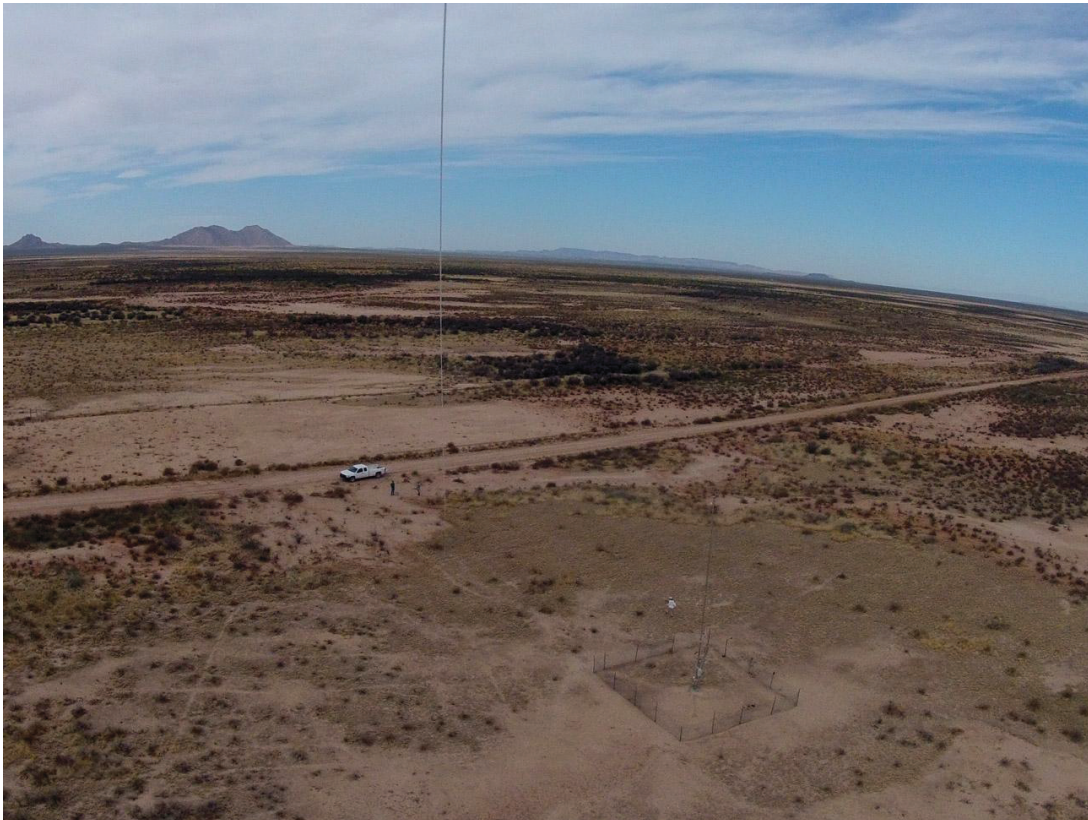


66

67 Figure 1. Study Site Location

68 The climate of Jornada is characteristic of the northern region of the Chihuahuan Desert with abundant
69 sunshine, low relative humidity, wide diurnal temperature ranges (average maxima are 36°C in June),

70 and variable precipitation both temporally and spatially. Potential evaporation is approximately 10 times
71 the average precipitation, which is $\sim 241 \text{ mm yr}^{-1}$ and occurs as localized thunderstorms during July,
72 August, and September. The site (106.69016°W , 32.58752°N) has variable cover of grasses and low
73 scrub (figure 2).



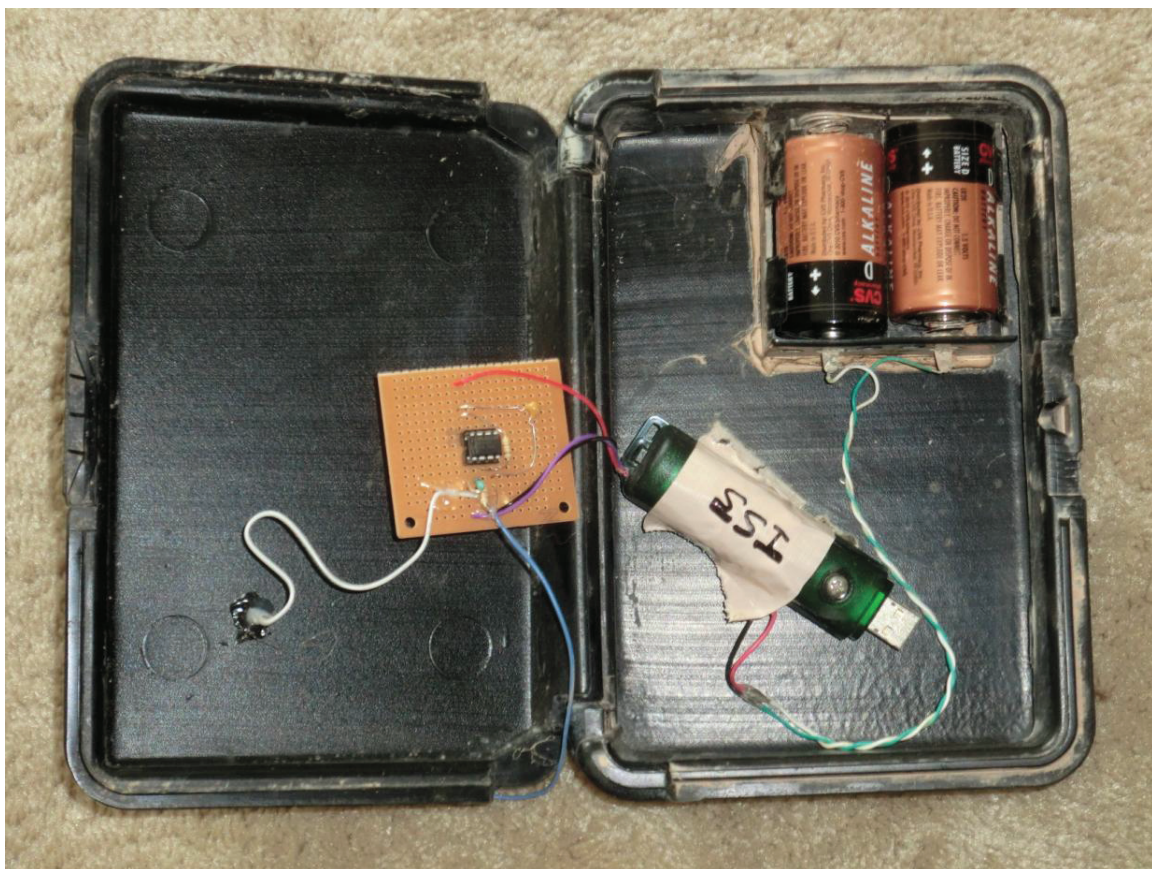
74

75 Figure 2. Aerial view of the field site, taken with a GOPRO digital camera lofted on a parafoil kite (the
76 kite string is visible just left of center). The area is flat, with partial cover of scrub land bushes. The
77 loggers were deployed just to the lower right of the square fence that protects an unrelated
78 meteorological installation. A vehicle and research personnel are visible for scale.

79

80 Following previous successful deployments (Lorenz et al., 2015; Lorenz, 2016) at Jornada, we use Gulf
81 Coast Data Concepts B1100 pressure loggers, which monitor a precision Bosch BMP085 pressure sensor
82 (recorded with a resolution of 1 Pa, or 0.01 mbar) with a microcontroller that logs the pressure data and
83 housekeeping temperature as ASCII files on a 2 GB microSD flash memory card. The whole unit operates

84 as, and its form factor resembles, a large USB memory stick, facilitating data transfer to a PC. As
85 described in Lorenz (2012), for this application the nominal single AA battery is replaced by a pair of
86 alkaline D-cells (figure 3), allowing unattended multi-month operation at sample rates of 2Hz or more.
87 The sensor and battery are installed in a plastic case, drilled to allow pressure equalization. An
88 augmentation to the standard B1100 that was made available to us by the manufacturer (see e.g. Lorenz
89 and Jackson, 2015) is the option to record an additional analog voltage (in the range 0 to 4.19 V) with
90 12 bit resolution at an interval of 1 s.



91
92 Figure 3. The instrumentation package comprises a datalogger (a large USB datastick) at lower right,
93 powered by two alkaline D-cells at upper right. An analog logging channel is wired to the point discharge
94 current sensor on the circuit board at left, which is grounded to a wire mesh (not shown). The white
95 wire at left is the input discharge wire.

96

97

98

99

100 For four loggers, this measurement channel was wired to a point discharge current sensor, using a
101 simple copper wire as a current collection antenna. Low voltage operation was required, since the
102 logger provided only 3.3V regulated power, and low current consumption was desired to permit long
103 duration operation. Further, low input bias current circuitry was required for this measurement: we
104 therefore selected the MAXIM MAX-407 electrometer-specification operational amplifier (<0.1 pA bias).
105 For this application, an aluminium mesh was attached to the case for grounding and screening, and to
106 limit surface charging (figure 3). The current-collecting electrode was a simple PVC-insulated tinned
107 copper wire projected vertically, further isolated from the case by a Teflon sleeve. About 7mm of tinned
108 conductor was exposed, 7cm above the upper surface of the case and thus 10cm above the ground
109 (figure 4). The unit was simply placed on the soil.



110

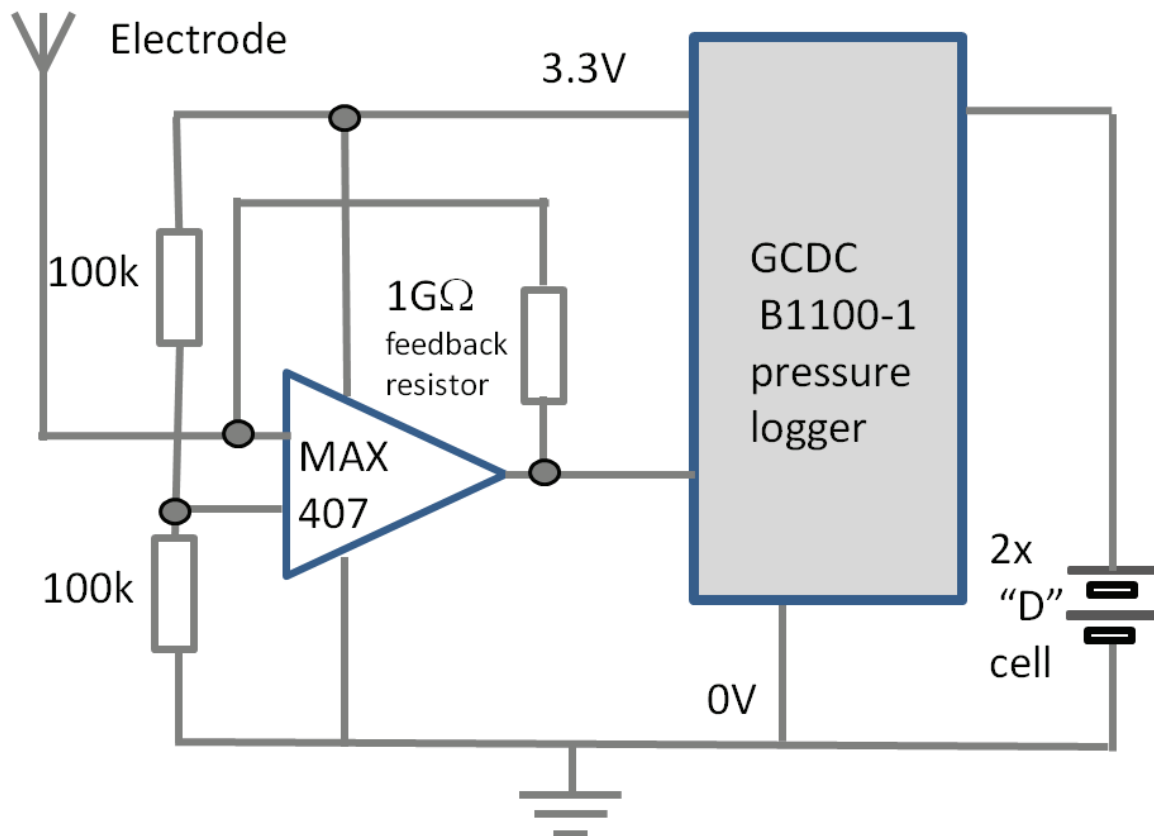
111 Figure 4. The logger as it was deployed in the field. The sensing wire projects ~ 7 cm up from the wire
112 mesh through an insulating Teflon sleeve (here hidden by some stiffening tape)

113

114

115 Because there may be a wide dynamic range of currents to measure, (e.g. Marlton et al., 2013 show
116 point discharge currents from fA up to μ A, depending on electrified cloud activity) two units (I51, I54)
117 were configured (figure 5) as a logarithmic current amplifier inspired by the point discharge sensor
118 design of Marlton et al. (2013). We used a pair of back-to-back near-infrared LEDs as the feedback
119 element in this instance. Although previous applications favoured green LEDs as having a stronger
120 response (Marlton et al., 2013; Acharaya and Aggarwal, 1996), their forward voltage drop was too high
121 for the present low-voltage operation, and so 940nm near-IR LEDs, with a smaller bandgap (~ 1.3 V) were
122 needed. Although ‘air-wiring’ the electrode to the op-amp is necessary for ultra-low current

123 measurements, this is much less necessary for the typical currents found in atmospheric point discharge
 124 (Marlton et al, 2013) and mechanical robustness for field deployment becomes the paramount
 125 consideration; the electrode wire was therefore simply soldered to the circuit board conventionally. For
 126 simplicity the temperature compensation circuits of Marlton et al. (2013) were not implemented.



127

128 Figure 5. Schematic diagram of the point discharge sensor current amplifier and pressure sensor logger
 129 setup. In this instance, the feedback component is a 1 G Ω resistor. In two other units this was replaced
 130 by a pair of LEDs. A 100nF decoupling capacitor (which is connected between across the op-amp
 131 supply rails) is not shown.

132

133 In addition, two units were configured as simple current amplifiers, one (a low sensitivity device) with a
 134 10 M Ω feedback resistor (giving a \sim 150nA full-scale reading for the \sim 1.5V voltage swing permitted by the
 135 sensor power supply) and another (a high sensitivity device) with a 1 G Ω resistor, giving a 1500 pA full-

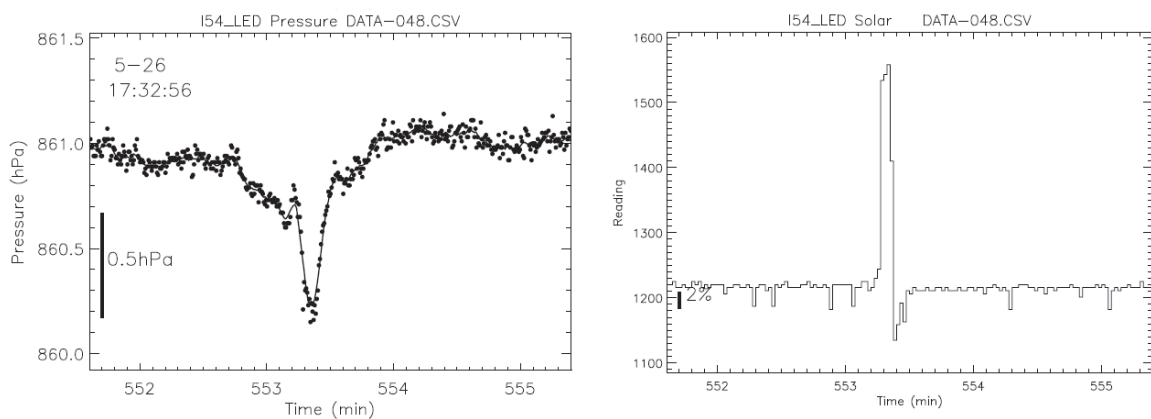
136 scale reading and a 1 pA resolution. All the loggers were deployed at the beginning of May, the start of
 137 the main dust devil season, and retrieved in mid-June, with the intent of avoiding monsoon rains.

138 It was found upon recovery that one of the LED-based sensors had become waterlogged, apparently by
 139 a rain event in early May, and no useable data were retrieved. The low sensitivity device operated as
 140 intended, but had inadequate sensitivity to detect electrical signatures associated with dust devils.

141 Although one wide-range LED unit did record a vortex encounter with a strong electrical signal (figure 6),
 142 the data from this unit was generally rather noisy and few coherent vortices were detected.

143

144



145

146 Figure 6. Dust devil encounter recorded by one of the LED-equipped units. (Left) pressure history over 4
 147 minutes during the afternoon of 26th May 2016, with a sharp dip of ~ 0.7 hPa (0.7 mbar) corresponding
 148 to a close passage of a dust devil vortex (the larger irregular dip may be due to a cycloidal migration path
 149 giving a complex distance history – e.g. Lorenz, 2013). (Right) a large electrical disturbance is seen
 150 coincident with the close passage of the devil : from the I-V characteristics of near-IR diodes (Acharaya
 151 and Aggarwal 1996) the ~ 320 mV signal is estimated to correspond to a current of the order of 1 nA.

152

153 The high sensitivity linear unit (in fact, employing the rather simple circuit of figure 6) appears to have
 154 functioned as intended, and recorded many dust devil encounters with clear electrical signatures.

155 Results from this device are discussed in the remainder of this paper.

156

157

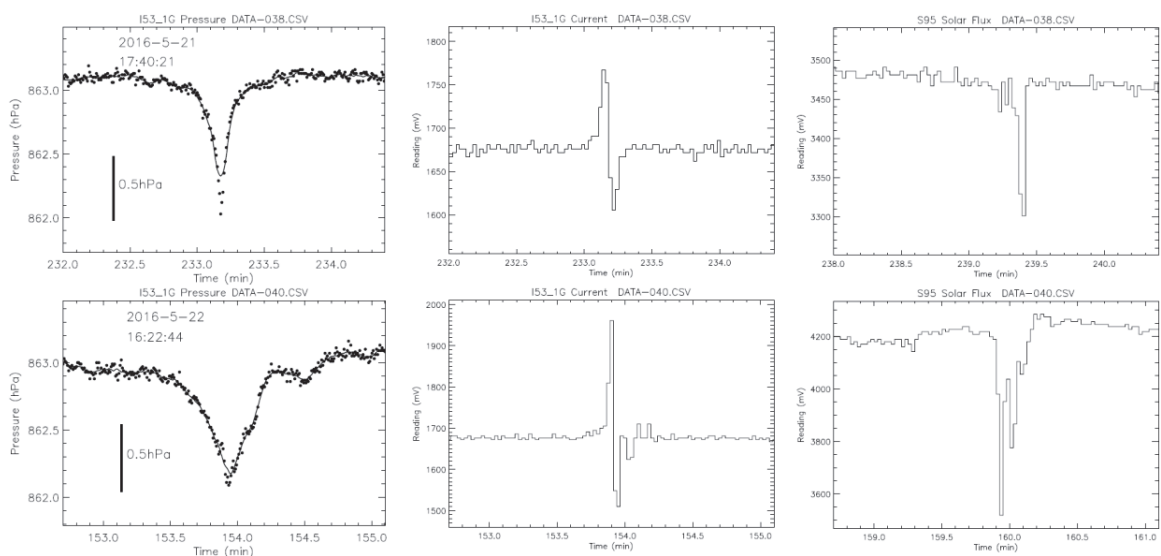
158 3. Results

159 The pressure record was used to identify close vortex passages, following the methodology of Lorenz
 160 and Jackson (2015), namely through a 6-s average reading being lower than the mean of the 30s before
 161 and after by 0.2 mbar. This algorithm fails to detect very brief pressure dips (due to very small and/or
 162 rapidly-advected vortices) and very long duration events, but maintains a low rate of false detections.

163

164 It is seen (figure 7) that a typical electrical signature is a positive voltage excursion of a couple of
 165 seconds (corresponding to a negative current, since the amplifier is in an inverting configuration),
 166 followed by an instantaneous swing to negative and then recovery back to zero. This is consistent with
 167 the base of dust devils having a generally negative space charge. Thus as the dust devil approaches, a
 168 positive current is induced, switching to a negative current as the dust devil makes closest approach and
 169 recedes. Only in a few instances (e.g. figure 8) was this pattern not seen, possibly because the event
 170 was so brief that the 1-s sampling interval failed to capture the approach phase.

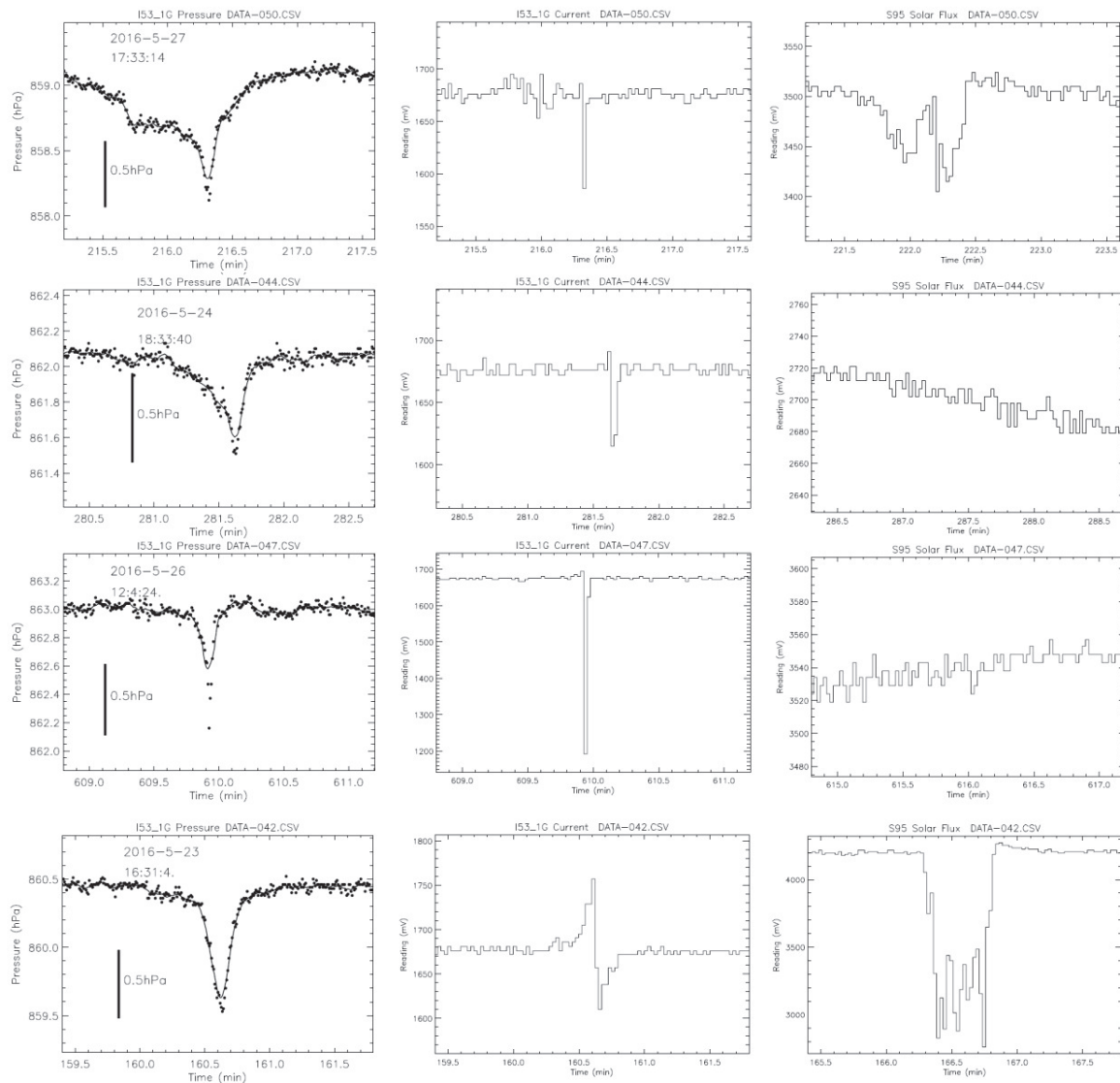
171



172

173 Figure 7. Two example encounters on 21 and 22 May respectively. The columns are (left to right) the
174 pressure recorded at the high sensitivity station, the voltage on the current monitor (the values
175 correspond to the current in pA (offset by 50% of the supply voltage, or ~1670 mV), and the short circuit
176 current of a solar cell on a nearby logger, illustrating the obscuration of sunlight by the dust plume
177 associated with the vortex (note that the periods shown are the same for each set of three plots : the
178 timebase of the solar cell is offset by 6 minutes : synchronization was checked by matching the pressure
179 record at the solar cell with that on the current meter). The 'heartbeat' shape of the current curve, and
180 the correlations of this event with the vortex pressure signal and the dust obscuration, are evident.

181



182
 183 Figure 8. Further example encounters, as figure 7. Top, the same event detected by the wide-range LED
 184 unit (figure 6) in this case recorded by the nearby $1\text{G}\Omega$ high sensitivity sensor. Only a brief main current
 185 excursion is seen, although with some irregular precursors. The solar record (right, again the difference
 186 in numeric timebase is not significant) indicates either multiple encounters with a meandering devil
 187 (Lorenz, 2013), or possibly a multi-core vortex or the two walls in a diametric encounter (Lorenz and
 188 Jackson, 2015). Lines 2 and 3 show brief, single-sided dips : there was no corresponding dust
 189 obscuration event, although this could be due to the non-colocation of the dust measurement. Bottom,
 190 again a ‘heartbeat’ signature, with the solar flux record showing a rather strong (35%) obscuration
 191 lasting some 30 seconds.

192

193 This characteristic pattern argues for a space charge in the dust plume being advected across the sensor:
194 although the logger is low on the ground such that the wire could be impacted directly by charged sand,
195 this appears not to be a significant factor in the signatures associated with vortex passage. Occasional
196 single-sample spikes of +/- 20 mV were seen that were not associated with measurable vortex passages,
197 and cannot be excluded as impacts of sand, grass or other debris. However, we note that the noise level
198 on the 1G Ω logger current channel was in any case around 10 mV (i.e. 10 pA) both day and night.

199

200 Ambient weather conditions were recorded at the nearby Jornada SCAN weather station operated by
201 the National Water and Climate Center
202 (<http://wcc.sc.egov.usda.gov/nwcc/site?sitenum=2168&state=nm>) and noted alongside the vortex
203 event parameters in table 1. Generally winds were from the south with average speeds of ~10 mph
204 (~5 m/s, typical for favorable conditions for dust devil formation) and the humidity was low.

205

206

Event #	File	Minute	Month	Day	Hour	Min	Pressure Drop (hPa)	Current (-ve, pA)	Current (+ve, pA)	Drop in sunlight (%)	Ave Wind Direction (°)	Max Wind Speed (mph)	Ave Wind Speed (mph)	Relative Humidity (%)
1	30	37.1	5	17	12	18	0.7	-98	40	0	113	23.9	12.9	24
2	32	20.4	5	18	12	3	0.4	-3	16	1	126	17.6	8.3	43
3	38	233.2	5	21	15	40	1.1	-65	97	5	209	23.1	10.4	9
4	40	153.9	5	22	14	23	0.9	-160	291	13	227	27.4	14.5	11
5	42	160.6	5	23	14	31	1	-60	87	33	225	26	13.5	10
6	44	281.5	5	24	16	34	0.6	-55	21	0	222	25.1	15.5	8
7	47	610	5	26	10	4	0.8	-478	25	0	229	27.2	15.6	15
8	50	216.4	5	27	15	33	0.9	-84	25	3	232	21.4	9.7	9
9	52	102.5	5	28	13	41	0.5	-3	16	1	196	25.3	13.5	8
10	52	232.2	5	28	15	51	0.4	-46	35	1	186	23.9	11.9	6
11	52	306.1	5	28	17	5	0.5	-3	11	2	177	18.9	8.4	6

207

208 Table 1. Events detected automatically and confirmed by manual inspection of the records, with extracted parameters. The events occurred
 209 in a two-week interval in the measurement period when conditions were favorable for dust devils. The humidity, average wind speed and
 210 direction and maximum wind for the clock hour including the event is added for reference (see text). Note that some precipitation was
 211 recorded at the weather station at 15:00 on 5/17/2016 and at 14:00 on 5/18/2016, shortly after events #1, and #2.

212

213

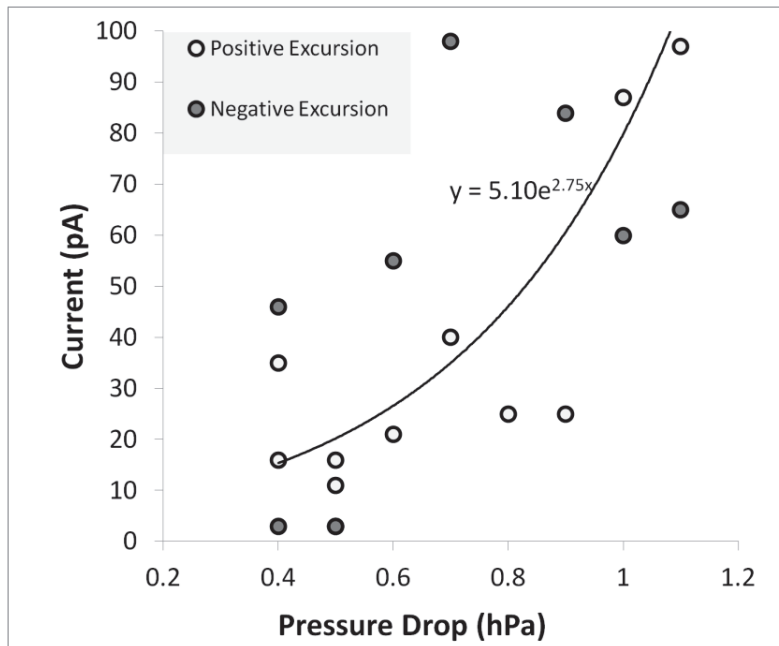
214 4. Discussion

215 It is seen that the electrical signature is much shorter in duration than the pressure excursion, which
216 varies approximately as $\sim R^2/(R^2+d^2)$ where R is the dust devil half-diameter and d is the distance from
217 the sensor to the center of the devil. (The dust devil diameter is obvious in well-formed cylindrical
218 vortices as the 'wall' of dust, and corresponds to a pressure drop equal to half that at the vortex center.)
219 This is not surprising, in that the spatial extent of the electrical disturbance would be expected to
220 correspond closely to that of the dust which is typically the half-pressure radius, whereas a detectable
221 pressure excursion typically extends several times further (to roughly where the pressure drop is a tenth
222 of that at the core).

223 Crozier (1970) note that pulses in observed electric field were observed when the dust loading was
224 temporarily enhanced when the devil encountered areas of enhanced dust availability and Esposito et
225 al. (2016) document a number of dust devil encounters in Morocco, showing that in general the dust
226 loading correlated with electric field perturbation, and the two were negatively correlated with relative
227 humidity. Fields of thousands to tens of thousands of V/m were recorded during dust devil encounters.

228 We would expect that in general the discharge current would correlate linearly with the local electric
229 field (e.g. Large and Pierce, 1956; Kirkman and Chalmers, 1957). Wind speed is also a significant factor in
230 influencing the current, although different expressions for this dependence, and the dependence on the
231 height of the point above the ground, have been proposed (e.g. Chalmers and Mapleson, 1955). It
232 should be noted, however, that the correlation of 'fair weather' point discharge current with windspeed
233 merely leads to an increase in the current for a given electrical field, and would not explain the change
234 in polarity (the 'heartbeat') we observe which appears to be associated with dust devil passage
235 specifically.

236



237

238 Figure 9. The maximum positive and negative discharge current is shown as a function of the core
 239 pressure drop. It is seen that both are correlated, although the data do not permit a robust
 240 discrimination of the functional dependence. An example exponential fit is shown for the positive
 241 excursion, but a linear dependence on pressure above some threshold value would also be an adequate
 242 fit. (NB the outlier, event #7, is not shown and is excluded from the fit).

243

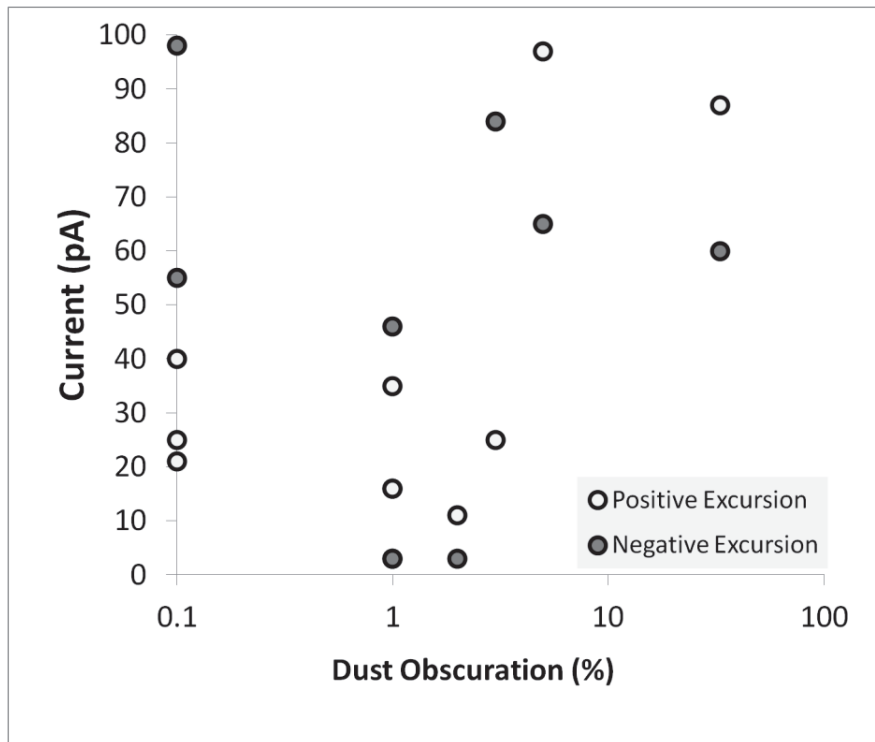
244

245 Figure 9 shows the correlation of the peak negative current with the peak pressure drop. Note that the
 246 pressure drops are slightly larger than typical : a survey at this same site in June 2013 (Lorenz et al.,
 247 2015) found that 0.4mbar encounters occurred at a rate of about 30 per 100 days, while 1 mbar
 248 encounters were about ten times less frequent.

249 We find some correlation (figure 9) between the optical effect of the dust loading (which was not
 250 directly determined, since the solar obscuration was measured at a site offset by about 15m from the
 251 point discharge sensor) and discharge current. We may note that Esposito et al. (2016) documented a
 252 somewhat linear correlation of electric field with dust loading for encounters with a fixed relative
 253 humidity.

254

255



256

257 Figure 10. Correlation of peak current with dust content measured nearby. The fact that the
 258 measurements were not co-located is probably the reason for the set of points with negligible (0.1% on
 259 this logarithmic plot) dust obscuration. When dust obscuration was detected, it seems positively
 260 correlated with the current.

261

262 The observation period was about 40 days, or ~ 4 million seconds, during which 11 events were detected
 263 with electrical disturbances of some tens of picoAmps each lasting 10 seconds or so. Thus conditions
 264 were disturbed for a fraction of about 3×10^{-5} of the time (30 millionths). This is in quite good agreement
 265 with the area fraction of about 1×10^{-5} , occupied by the typical dust devil population on Earth (e.g. Lorenz
 266 and Jackson, 2016) described by a -1.6 cumulative power law in diameter between 1 and 100m in
 267 diameter. It follows that the time-averaged current from a point is $\sim 10^{-16}$ A.

268 The introduction of these currents to exposed conductors may have implications for the operation of
269 unattended ground sensors for security applications. If these dust-devil-triggered currents cause
270 spurious detections, a false alarm rate of ~ 0.25 /day during dust devil season may be expected.

271

272

273 5. Conclusions

274 Field testing has demonstrated that a very simple and compact sensor circuit can make useful
275 measurements of dust devil electrical properties. The compact and simple electrode and amplifier
276 configuration, presently arranged as a point discharge current meter, could be modified to measure
277 electric fields, or could be made more sensitive to small currents. The configuration shown here gives
278 robust indication of dust, and could be adapted to e.g. operation on an airborne platform such as an
279 Unmanned Aerial Vehicle (UAV), and is inexpensive enough (unlike a conventional field mill) to allow its
280 replication in large numbers, in principle permitting multiple measurements using an array of sensors.
281 An important step in future work would be to compare the current with independent electric field
282 measurements. One might hope in a more extended campaign to be able to resolve the vortex 'wall'
283 where dust density is locally high.

284

285

286

287 Acknowledgements

288 This work was funded by NASA through the Mars Fundamental Research Program grant number
289 NNX12AI04G. We thank Martina Klose for assistance in the field. We thank the Astronomy Department
290 of NMSU for assistance with shipping and the NASA Planetary Data System Atmospheres Node for
291 hosting dust devil data. Additional support was provided by Jornada Basin LTER (supported by National
292 Science Foundation Grant DEB-1235828). KAN acknowledges a NERC Independent Research Fellowship
293 (NE/L011514/1).

294

295

296 References

- 297 Acharya, Y.B. and Aggarwal, A.K., 1996. Logarithmic current electrometer using light emitting
298 diodes. *Measurement Science and Technology*, 7(2), 151-156
- 299 Atreya, S. K.; A.-S. Wong, N. O. Renno, W. Farrell, G. Delory, D. Sentman, S. Cummer, J.
300 Marshall, S. C. Rafkin, D. C. Catling,; 2006. Oxidant Enhancement in Martian Dust Devils and
301 Storms: Implications for Life and Habitability, *Astrobiology*, Volume 6, Issue 3, pp. 439-450.
- 302 Baddeley, P. F. H. (1860), *Whirlwinds and Dust Storms of India*, Bell and Daldey, London.
- 303 Balme, M. and R. Greeley, 2006. Dust Devils on Earth and Mars, *Reviews of Geophysics*, 44,
304 RG3003
- 305 Barth, E.L., Farrell, W.M. and Rafkin, S.C., 2016. Electric field generation in Martian dust devils.
306 *Icarus*, 268, pp.253-265.
- 307 Chalmers, J. A. and W. W. Mapleson, 1955. Point-discharge currents from a captive balloon, *J.*
308 *Atmospheric Terrestrial Physics*, 6, 149=159
- 309 Crozier, W.D., 1964. The electric field of a New Mexico dust devil. *Journal of Geophysical*
310 *Research*, 69(24), 5427-5429.
- 311 Delory, G. T., W.M. Farrell, S.K. Atreya, N.O. Renno, A.-S. Wong, S.A. Cummer, D.O. Sentman,
312 J.B. Marshall, S.C.R. Rafkin, D.C. Catling,2006. Oxidant Enhancement in Martian Dust Devils and
313 Storms: Storm Electric Fields and Electron Dissociative Attachment, *Astrobiology*, Volume 6,
314 Issue 3, pp. 451-462.
- 315 Ellehoj, M. D. , H. P. Gunnlaugsson, P. A. Taylor, H. Kahanpää, K. M. Bean, B. A. Cantor, B. T.
316 Gheynani, L. Drube, D. Fisher, A.-M. Harri, C. Holstein-Rathlou, M. T. Lemmon, M. B. Madsen,
317 M. C. Malin, J. Polkko, P. H. Smith, L. K. Tamppari, W. Weng, and J. Whiteway, Convective
318 vortices and dust devils at the Phoenix Mars mission landing site, *Journal of Geophysical*
319 *Research*, 115, E00E16, 2010

- 320 Esposito, F., Debei, S., Bettanini, C., Molfese, C., Arruego Rodriguez, I., Colombatti, G., Harri,
321 A.M., Montmessin, F., Wilson, C., Aboudan, A. and Abbaki, S., 2014. The DREAMS Experiment of
322 the ExoMars 2016 Mission for the study of Martian environment during the dust storm Season.
323 LPI Contributions, 1791, p.1246.
- 324 Esposito, F., Molinaro, R., Popa, C.I., Molfese, C., Cozzolino, F., Marty, L., Taj-Eddine, K., Di
325 Achille, G., Franzese, G., Silvestro, S. and Ori, G.G., 2016. The role of the atmospheric electric
326 field in the dust-lifting process. *Geophysical Research Letters*. 43, 5501–5508,
327 doi:10.1002/2016GL068463
- 328
- 329 Farrell, W. M. et al. (2003) "A simple electrodynamic model of a dust devil" *Geophysical*
330 *Research Letters* 30, 2050.
- 331
- 332 Farrell, W. M. et al. (2006) "A model of the ULF magnetic and electric field generated from a
333 dust devil" *Journal of Geophysical Research* 111, E11004
- 334
- 335 Harrison, R.G., Barth, E., Esposito, F., Merrison, J., Montmessin, F., Aplin, K.L., Borlina, C.,
336 Berthelier, J.J., Déprez, G., Farrell, W.M. and Houghton, I.M.P., 2016. Applications of electrified
337 dust and dust devil electrodynamics to Martian atmospheric electricity. *Space Science Reviews*,
338 pp.1-47.
- 339 Kirkman, J.R. and Chalmers, J.A., 1957. Point discharge from an isolated point. *Journal of*
340 *Atmospheric and Terrestrial Physics*, 10(5-6), 258-265.
- 341 Kok, J. F. and Renno, N. O. (2009) "Electrification of windblown sand on Mars and its
342 implications for atmospheric chemistry" *Geophysical Research Letters* 36, L05202.

- 343 Large, M.I. and Pierce, E.T., 1957. The dependence of point-discharge currents on wind as
344 examined by a new experimental approach. *Journal of Atmospheric and Terrestrial Physics*,
345 10(5-6), 251-257.
- 346
- 347 Lorenz, R. D., 2012. Observing Desert Dust Devils with a Pressure Logger, *Geoscientific*
348 *Instrumentation, Methods and Data Systems*, 1, 209–220
- 349
- 350 Lorenz, R. D., 2013. Irregular Dust Devil Pressure Drops on Earth and Mars: Effect of Cycloidal
351 Tracks, *Planetary and Space Science*, 76, 96–103, 2013
- 352
- 353 Lorenz, R. D., 2016. Heuristic Estimation of Dust Devil Vortex Parameters and Trajectories from
354 Single-Station Meteorological Data: Application to InSight at Mars, *Icarus*, 271, 326-337
- 355
- 356 Lorenz, R. D. and B. K. Jackson, 2015. Dust Devils and Dustless Vortices on a Desert Playa
357 Observed with Surface Pressure and Solar Flux Logging, *GeoResJ*, 5, 1-11
- 358
- 359 Lorenz, R. D. and B. K. Jackson, 2016. Dust Devil Populations and Statistics, *Space Science*
360 *Reviews*, in press
- 361
- 362 Lorenz, R.D., Neakrase, L.D. and Anderson, J.D., 2015. In-situ measurement of dust devil activity
363 at La Jornada Experimental Range, New Mexico, USA. *Aeolian Research*, 19, 183-194.
- 364
- 365 Lorenz, R. D., M. R. Balme, Z. Gu,, H. Kahanpää, M. Klose, M. Kurgansky, M. R. Patel, D. Reiss, A.
366 P. Rossi, A. Spiga, T. Takemi, W. Wei. 2016. History and Applications of Dust Devil Studies, *Space*
367 *Science Reviews*, in press doi:10.1007/s11214-016-0239-2
- 368
- 369 Marlton, G., R. G. Harrison and K. Nicoll, 2013. Note: Atmospheric point discharge current
370 measurements using a temperature-compensated logarithmic current amplifier, *Review of*
371 *Scientific Instrumentss*, 84, 066103

372

373 Nicoll, K. A., R. G. Harrison and Z. Ulanowski, Observations of Saharan dust layer
374 Electrification, Environment Research Letters, 6, /014001, 2011. doi:10.1088/1748-
375 9326/6/1/014001

376

377 Snow, J. T. and T. McClelland, Dust devils at White Sands Missile Range, New Mexico 1.
378 Temporal and Spatial Distributions, 1990. J. Geophysical Research, 95, 13,707-13,721