# Martian Dust Abrasion Damage on Solar Arrays: HALT Experimental Investigation and Opportunity Rover Performance Analysis

Lyndsey McMillon-Brown, Timothy J. Peshek, AnnaMaria Pal, and Jeremiah McNatt

NASA Glenn Research Center, Cleveland, OH 44135, USA

***Abstract* — We investigated the utility of ground-based highly accelerated life testing (HALT) on epitaxial lift-off (ELO) triple-junction coverglass interconnected cells (CICs) after exposure to simulated Martian dust storms. Dust storm impingement was replicated by sandblasting CICs with Mars dust simulant replicating conditions similar to the weather conditions reported by the Viking landers. We observed that even in cases when there are no observable open circuit voltage ($V_{OC}$) losses, the minority carrier lifetime is reduced. Short circuit current ($J_{SC}$) losses can be recovered upon cleaning, suggesting $J_{SC}$ losses are not linked to permanent damage, like cell cracking. This suggests a permanent degradation could be determined by quantifying the difference between recoverable and non-recoverable power loss. We mined field data from the Mars Exploration Rover, Opportunity and extracted a degradation rate to compare to our experimental data. We found exceptional agreement between 4.9 Martian years of mined field data (9.4%) and the irreversible damage observed in our HALT experiment (9.7%). We demonstrate that the laboratory method for exposing CICs to Martian dust storm conditions well represents the physical reality of long duration CIC operation on Mars.**

## I. Introduction

The atmosphere of Mars contains suspended dust, the amount of which varies, increasing when global or local dust storms raise dust into the atmosphere and decreasing in mild conditions.[1] The levels of dust suspended in the atmosphere rarely reach zero. These conditions pose challenges for the operation of solar cells, the selected power source for current and future missions for Mars exploration. [2-4]

Here we investigate the effects of Martian dust storm conditions on epitaxial lift off (ELO) triple-junction solar cell CICs exposed to simulated Martian dust storms and via analogous simulation. This work is a continuation of an earlier investigation reported in the 46th IEEE Photovoltaic Specialist Conference Proceedings [1]. This continuation focuses on the utility of a highly accelerated lift testing (HALT) apparatus as a platform to discern reversible vs irreversible CIC degradation in Mars dust storm conditions. Further, this work quantifies how the CIC degradation achieved by HALT simulation apparatus by comparing results to Opportunity Rover field data. Using the experimental and field data we disentangle irreversible and reversible power losses. We implement physical models to reduce variance in the mined rover dataset. We seek to quantify the resulting power output and observable irreversible damage caused by Martians dust storms in situ and via HALT simulation. We simulated Martian dust storms on CICs to develop better predictions of photovoltaic performance in adverse Martian weather conditions. We employed the five-parameter, or single-diode, model of solar cell operation to identify the source of observed losses, specifically seeking to reveal if device performance losses can be solely attributed to $J_{SC}$ reductions caused by settled dust [2]. Finally, we identify the resulting CIC degradation modes caused by Mars dust storms and we show the resulting impact on minority carrier lifetime. In the interest of brevity, we present an abbreviated version of the investigation. The detailed continuation is published in reference [3].

## II. Methods

We developed a webscraper routine to pull publicly available data from the mars.nasa.gov [4] website for the Opportunity rover. The webscraper conducted a semantic analysis to seek the terms "watt-hours" and parse the output such that string literals with the search term could be gathered. Next, the scraper parsed the phrases seeking measurements of the atmospheric opacity, $tau$, "dust factor", and dates (in Sols). Ultimately we acquired 4.9 Martian years of data from the webscraper. The dust factor, denoted $D$, is a measure of the loss factors of the array. That is, it is essentially defined by: $D = E_{PV}/E_{in}$, where $E_{PV}$ is the daily energy produced by the Opportunity solar arrays in watt-hours and $E_{in}$ is the estimated power input to the system as calculated from the position, $tau$, and BOL array efficiency, $\eta_0$. Thus, $E_{in} = 6(G_{bh} + G_{dh})\eta_0$, where $G_{bh}$ and $G_{dh}$ are the beam and diffuse insolation on a horizontal surface on the Martian surface, as determined by Appelbaum and Flood [5]. This expression is simplified due to the fact that the Opportunity rover is near the equator.

Note that the energy data are highly variable and subject to many factors including seasonality and a time-dependent dust occlusion/removal process that is wind driven and correlated with the suspended dust in the atmosphere [6], [7] and therefore a strict analysis of the energy output is challenged by variability. However the dust factor time series, $D(t)$ constrains this variability and implicitly contains the loss factors over time and can be rewritten as $D(t) = E_{PV}(t)/6(G_{bh}(t) + G_{dh}(t))\eta(t)$. Since $D(t)$ and $E_{PV}(t)$ are the time series mined from the dataset, we defined a new variable, BOL yield, $Y_0$, that is defined such that: $Y_0(t) = E_{PV}(t)/6(G_{bh}(t) + G_{dh}(t))\eta_0$, where $(G_{bh}(t) + G_{dh}(t)$ is calculated

using the method of Appelbaum and Flood. Therefore the ratio of $\frac{Y_0(t)}{D(t)} = \frac{\eta(t)}{\eta_0}$.

## III. Results and Discussion

The removal of the variance due to seasonality in the dataset of the Opportunity rover was critical in order to extract a first order degradation rate. The seasonality in irradiance due to orbital motion is easily taken into account by estimating the irradiance variation over a Martian year at the top of the atmosphere and using the value of tau and invoking Beer's law to estimate $G_{bh}$ [5]. However, we noted that the resultant dataset, which is a contribution of diffuse irradiance and dust coverage is sinusoidal (Fig 1). Various physics based models of estimating diffuse irradiance upon a surface are published, including scattering off of aerosols, however estimates of the diffuse irradiance on the surface of Mars have been published and modeled. We utilized those datasets and modeled the data with a multiple linear regression models such that a linear model of the equatorial region, up to a tau of approximately 1.0 could be determined with acceptable error. The acceptable error was defined as a maximum of the autocorrelation function of the energy dataset with the yield function. That is, where the autocorrelation function contains a maximum at 0 slew (Fig 2a). In this way we suggest the maximum variance can be accounted for with diffuse irradiance, and subsequently the yield function more accurately determined for a subset of the data where tau is constrained to be less than unity.

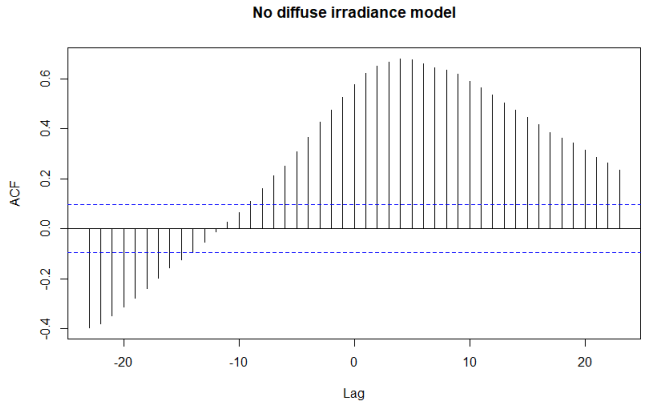
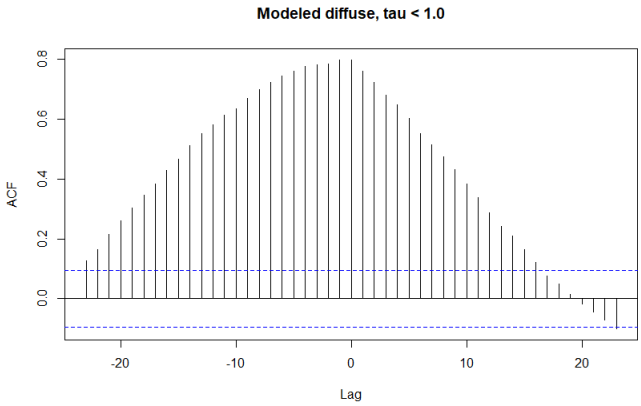



**Figure 1.** The autocorrelation function between the dust factor and Tau as a function of daily slewing.

The resultant dataset showed a clear decay in performance although overall the data still indicated a sinusoidal behavior that we associate with seasonal affects on dusting and cleaning events. Therefore this approach results in the data not only indicating typical probabilities of dust coverage on horizontal surface and subsequent removal through natural processes but the non-recoverable decay of performance over time. The non-recoverable degradation is modeled as a linear degradation rate, and the uncertainty on the slope of that model excludes zero with a confidence level of >99%, ($p < 0.00026$) (Fig 2b).

**a)**




**b)**

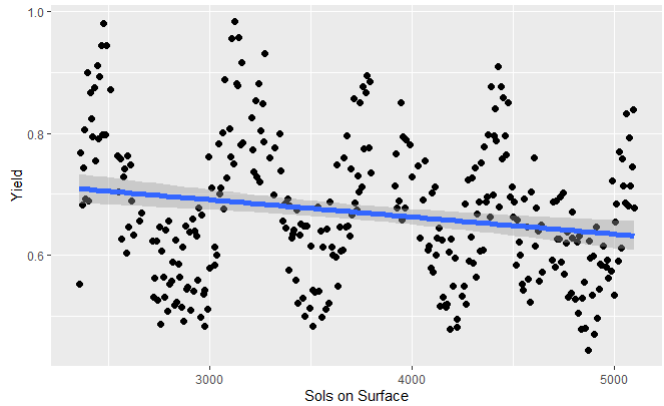



**Figure 2. a)** Autocorrelation function of a modeled data set with acceptable error. **b)** Linear fit to photovoltaic array yield as a function of Sols on Martian surface (blue) with confidence bands. The negative slope indicates permanent cell degradation.

## IV. Conclusion

Here we present detailed explanation for the webscraper routine used to gather the Opportunity Rover report out data. We share the methods implemented to remove seasonality from the rover data. We present our modeled data utilized to determine a linear model of the Mars equatorial region. The resulting photovoltaic yield of the dataset indicate a clear performance decay. This computational degradation analysis of mined rover field data has strong comparison between irreversible degradation observed in our laboratory experiments [3]. We thus have demonstrated that the laboratory method for exposing CICs to Martian dust storm conditions well represents the physical reality of CIC exposure to the Martian environment.

## References

[1] L. McMillon-Brown, T. J. Peshek, A. Pal, and J. McNatt, "Dust Abrasion Damage on Martian Solar Arrays: Experimental Investigation and Opportunity Rover Performance Analysis," in

*2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, Jun. 2019, pp. 2838–2844. doi: 10.1109/PVSC40753.2019.8980876.

[2] T. J. Peshek *et al.*, "Insights into metastability of photovoltaic materials at the mesoscale through massive I–V analytics," *J. Vac. Sci. Technol. B*, vol. 34, no. 5, p. 050801, Aug. 2016, doi: 10.1116/1.4960628.

[3] L. McMillon-Brown, T. J. Peshek, A. Pal, and J. McNatt, "A study of photovoltaic degradation modes due to dust interaction on Mars," *Sol. Energy Mater. Sol. Cells*, vol. 221, p. 110880, Mar. 2021, doi: 10.1016/j.solmat.2020.110880.

[4] mars.nasa.gov, "Mars Exploration Rovers." https://mars.nasa.gov/mer/ (accessed May 13, 2020).

[5] J. Appelbaum and D. J. Flood, "Solar radiation on Mars," *Sol. Energy*, vol. 45, no. 6, pp. 353–363, 1990.

[6] G. A. Landis and P. P. Jenkins, "Measurement of the settling rate of atmospheric dust on Mars by the MAE instrument on Mars Pathfinder," *J. Geophys. Res. Planets*, vol. 105, no. E1, pp. 1855–1857, 2000.

[7] R. Greeley and R. M. Haberle, "Sand and dust on Mars," 1991.

## APPENDIX: WEB SCRAPER CODE

```
#### FUNC TO MINE DATA FROM MER WEBSITES ###
####================================
ParseMER = function(year){
  if(year < 2015){
    site =  paste("https://mars.nasa.gov/mer/mission/rover-status/opportunity/", as.character(year), "/all/", sep = "")
  }
  if(year >=2015){
    site = paste("https://mars.nasa.gov/mer/mission/rover-status/opportunity/recent/all/?y=",as.character(year), sep= "")
  }

  html.site<-readLines(con = site, warn=FALSE, skipNul = TRUE)
  text.site = unlist(strsplit(html.site[grep("watt", html.site)], split = "<p>"))
  vec1 = grep("watt", text.site)
  text.mine = text.site[vec1]

  parse.mine = NULL
  for (i in 1:length(text.mine)){
    string.mine = unlist(strsplit(x = text.mine[i], split = "<br>"))
    parse.mine = c(parse.mine, string.mine[grep("TRUE", str_detect(string = string.mine, pattern = "As of Sol"))])
  }
  return(parse.mine)
}

#### FUNC TO PARSE DATA ###
####================================
=

MER.dat.split = function(i){
  string = MER.dat[i]
  Dat.Test5 <- strsplit(x = string, split = " ")
  my.dat = c(as.numeric(Dat.Test5[[1]][grep("Sol", Dat.Test5[[1]])[1]+1]),
             as.numeric(Dat.Test5[[1]][grep("watt-hours", Dat.Test5[[1]])[1]-1]),
             as.numeric(Dat.Test5[[1]][grep("Tau", Dat.Test5[[1]])[1]+2]),
             as.numeric(substr(Dat.Test5[[1]][grep("Dust-factor", Dat.Test5[[1]])[1]+2], 1,4))
  )
  return(my.dat)
}

#### FUNC TO CLEAN UP SEMANTICS ###
####================================
=
LibraryFun = function(dat_test2){
  dat_test2 <- gsub(".<br />", " ", dat_test2)
  #dat_test2 <- gsub(". ", " ", dat_test2)
  # dat_test2 <- gsub(". </p>", " ", dat_test2)
  # dat_test2 <- gsub(".</p>", " ", dat_test2)
  dat_test2 <- gsub("  ", " ", dat_test2)
  dat_test2 <- gsub(", ", " ", dat_test2)
  dat_test2 <- gsub("As of the last returned telemetry on Sol", "As of Sol", dat_test2)
  dat_test2 <- gsub(":", " ", dat_test2)
  dat_test2 <- gsub("tau", "Tau", dat_test2)
  dat_test2 <- gsub("dust", "Dust", dat_test2)
  dat_test2 <- gsub("sol ", "Sol ", dat_test2)
  dat_test2 <- gsub("Watt ", "watt ", dat
```

```
_test2)
  dat_test2 <- gsub("-", " ", dat_test2)
  dat_test2 <- gsub("Dust factor", "Dust-
factor", dat_test2)
  dat_test2 <- gsub("watt hours", "watt-h
ours", dat_test2)
  return(dat_test2)
}


#### FUNC TO MESH AEROCENTRIC ANGLE WITH
MISSION SOLS ###
####================================
=
AeroCentricAngle = function(){
  L_S = rep((seq(0:668)-1)/668*360, 6)
  L_S = L_S[530:3759]
  # L_S_test = (c(530:3759)-1)/668*360
  # plot(y = data$G, x = data$Sols)
  # lines(x = Sols_max, y = myfun(L_S_tes
t, 280) , col = 'red')
  # plot(L_S, Sols_max)
  Sols_max = c(min(MartianDat.scaled.sub$
Sols):max(MartianDat.scaled.sub$Sols))
  L_S2 = MartianDat.scaled.sub$Sols
  for (i in 1:length(MartianDat.scaled.su
b$Sols)){
    L_S2[i] = L_S[which(Sols_max == Marti
anDat.scaled.sub$Sols[i])]
  }
  return(L_S2)
}
```