Measuring Neutrons and Gamma Rays on Mars - The Mars Science Laboratory Radiation Assessment Detector MSL/RAD

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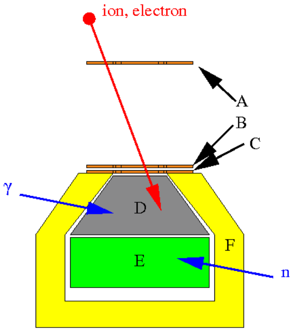

Figure 1: The RAD instrument concept. Charged particles are measured with the multiple $\mathrm{d}E/\mathrm{d}x$ vs. total E method, whereas neutrals (gammas and neutrons) are measured in detectors D and E only. The high-density (D) and high-proton-content (E) scintillators are encapsulated by a highly efficient anti-coincidence shield (F).

Introduction: The Mars Science Laboratory (MSL) mission's Radiation Assessment Detector (RAD) will measure the radiation environment on the Martian surface. One of the difficult measurements is that of the neutral radiation component consisting of neutrons and gamma rays. Different from Earth, this neutral component contributes substantially to the total dose on the planetary surface, principally because the Martian atmosphere is so thin.

The RAD instrument is capable of measuring neutral particles through a combination of sensitive anti-coincidence and organic and inorganic scintillator materials. Figure 1 shows a schematic view of RAD and explains its basic functions. In this work, we will investigate methods for deriving separate statistical estimates for the neutron and gamma radiation on Mars from RAD measurements.

Background

The problem of inverting measured neutron and gamma data is a non-trivial task. As with all data inversions, one generally assumes that the measurement process can be described by a system of linear equations. In fact, these follow from a Fredholm equation which can be discretized into a set of linear equations, $\mathbf{A}\vec{f} = \vec{z}$, where the matrix $\mathbf{A}$ describes the instrument response function (IRF), $\vec{f}$ the underlying, but unknown, "real" physical parameters, i.e., the spectrum, and $\vec{z}$ the measured data. The inversion of this deceptively simple-looking set of equations is in fact a key example of an ill-posed or inverse problem. Such problems are notoriously difficult to solve. Based on previous work [1, 2] we are currently developing inversion schemes for RAD data which are based on various techniques (see [2]). Key to any sucessful inversion scheme is accurate knowledge of the instrument response function.

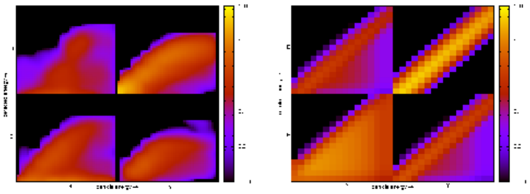

Figure 2: Instrument response functions of MSL/RADs CsI(Tl) (top panels) and BC-432m (bottom panels) detectors to neutrons (left-hand panels) and gamma rays (right-hand panels). The left hand panel shows the current best mel, the right-hand panel a highly simplified version used for software testing.

Instrument Response Function

Figure 2 shows the istrument response function of MSL/RAD's CsI(Tl) and BC-432m (plastic) detectors to neutrons and gamma rays. The IRF was simulated with the CERN-package GEANT in which relevant processes can be included. The right-hand panel shows a highly simplified version used for software testing. The more realistic IRF is shown in the left side of this figure. The upper half of the panel shows the CsI(Tl) response, the bottom half the plastic (BC-432m) response. The left-hand panels show the reponses to neutrons while the right-hand panels show the responses to gamma rays. The response of CsI(Tl) for gamma rays (top right panel) is close to diagonal and in stark contrast to the CsI(Tl) response to neutrons. The reason for the difference lies in the detailed physics of the interactions of gamma rays and neutrons with CsI(Tl). The bottom two panels show the responses for RAD's plastic scintillator to neutrons (left) and gamma rays (right). Here, the left-hand panel is "better" than the right-hand one, again because of the different physics

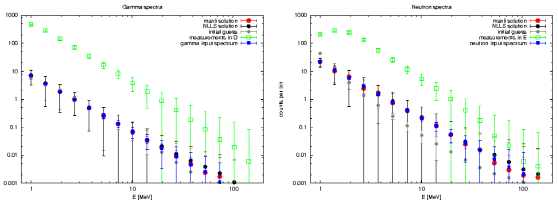

Figure 3: Input (blue), measurements (green), initial guess (grey), maximum-likelihood (red) and NNLS (black) spectra for gammas (left) and neutrons (right).

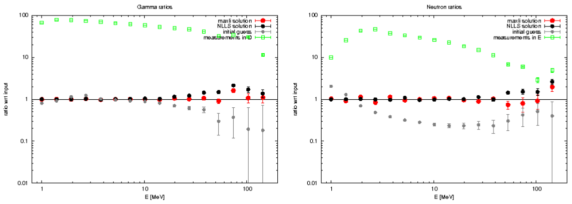

Figure 4: Ratios of measurements (green), initial guess (grey), maximum-likelihood (red) and NNLS (black) spectra with respect to an input spectrum for gammas (left) and neutrons (right).

of the neutron and gamma-ray interactions with this proton-rich scintillator.

Given the measurements, $\vec{z}$, and the IRF, $\mathbf{A}$, we can invert $\vec{z}$ to obtain the neutral-particle spectra, $\vec{f}$. A similar analysis has been applied to data from the interplanetary SOHO/EPHIN and STEREO/SEPT instruments [1].

The diffculty in solving this 'simple' set of linear equations lies in the following points. First, particle measurements are a statistical measurement with vector elements z_i distributed around an expectation value, λ_i. Depending on the exact vaues of $\vec{z}$ it is then well possible to obtain unphysical values for $\vec{f}$ from a straight-forward inversion process. Second, the matrix describing the IRF is itself derived from a Monte-Carlo simulation with its own statistical uncertainties. Third, we use the IRF to invert the 'measurement equation', but we don't know the true underlying IRF. There may well be systematic uncertainties or even errors associated with $\mathbf{A}$ which we do not know about and, therefore, can not take into consideration.

Using the highly simplified IRF shown in the right half of Fig. 2, we have tested two different methods for inverting the 'measurement equation', $\vec{z} = \mathbf{A}\vec{f}$. For this we have assumed that the simplified IRF, $\mathbf{A}$, is a correct model for RAD (we know it isn't, but from a purely mathematical point of view we don't need to care). On the one hand, we used a constrained non-linear least squares(NLLS) algorithm which is implemented in `numpy` as `fmin_l_bfgs_b` [3]. The constaints were $f_i \geq 0, \forall i$. The other method used the same minimization routine, but with an objective function which is appropriate for situations with only few counts in a spectrum, i.e., $\sum_i \left[z_i \ln \lambda_i - \lambda_i - \ln(z_i!)\right]$.

The results are shown in Figs. 3 which shows results for gammas and neutrons, respectively. We generated 1000 spectra with an expectation value of 1000 particles each. Their average and standard deviation is shown in blue, the inversion using maximum-likelihood with Poissonian statitics is shown in red, NLLS in black. Average measurements in detectors D or E (CsI or BC-432m) are plotted in green, the average initial guess in grey. As is easily seen, there is a reasonable overall agreement of inversion and input. It is hard to see systematic differences. These are more easily seen if one plots the ratios of measurements, initial guess, maximum-likelihood and NNLS spectra with respect to the modeled input spectra. This is shown in Fig. 4.

As expected, the maximum-likelihood method does an overall better job, especially where counts are rare.

Initial work on vaying the IRF shows that both methods are sensitive to the IRF used. While a more detailed IRF such as that shown in the left half of Fig. 2, i.e., a larger matrix, obviously requires more computing time, but perhaps unexpectedly, the difference in NNLS and the maximum-likelhood solutions are also less clear cut (not shown here).

Summary, Conclusions, and Outlook

We have investigated a non-linear-least-squares method and a maximum-likelihood methods based on the expected underlying Poissonian statistics to invert artificial neutral particle data modeled with MSL's RAD instrument response function. for a highly simplified IRF, the maximum-likelihood method yields more consistent results than the constrained NNLS method. This is not unexpected, but comes at the cost of additional software complexity and computation time. Future work will need to incorporate effects of both statistical as well as possible systematic uncertainties in the IRF.

References: [1] E. Böhm, et al. (2007) *Astron& Astrophys* 473:673 http://dx.doi.org/10.1051/0004-6361:20077216 `doi`. [2] A. Kharytonov, et al. (2009) *Astron & Astrophys* 495:663 http://dx.doi.org/10.1051/0004-6361:200810854 `doi`. [3] R. H. Byrd, et al. (1995) *SIAM Journal on Scientific and Statistical Computing* 16.5:1190 .

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