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# The Angle Detecting Inclined Sensors (ADIS) System: Measuring particle angles of incidence without position sensing detectors

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**Abstract.** We report on a novel system, the Angle Detecting Inclined Sensors (ADIS), for determining the angles of incidence of Solar energetic particles, Galactic cosmic rays and anomalous cosmic rays. This system would be especially applicable to compact high resolution energetic particle telescopes. The response of charged particle detectors varies with particle pathlength, which depends on angle of incidence. Achieving good elemental and isotopic resolution requires correcting for this effect. ADIS consists of three detectors, two of which are inclined at an angle to the telescope axis, forming the first detectors in a multi-element telescope. By comparing the signals from the ADIS detectors, and using the computable angle dependent pathlengths through the detectors, the angle of incidence may be determined. The ADIS system thus can replace hodoscopes using conventional position sensing detectors (PSD's). PSD's add significant complexity and require additional electronics, increasing instrument mass, power usage and, in many cases, telemetry requirements. We derive simple equations for the incident particle charge and trajectory. These calculations are well within the capabilities of even the slowest on-board processors. We present Monte-Carlo modeling of such an instrument to demonstrate the system's capabilities.

## 1. Introduction

The detection and identification of high energy nuclei in space is essential to the study of Solar Energetic Particles (SEP), Galactic Cosmic Rays (GCR) and Anomalous Cosmic Rays (ACR). Instruments flown on spacecraft and high altitude balloons are usually severely constrained as to instrument mass, power and often available telemetry rate. At the same time, sufficient detector area and acceptance angle are crucial to collecting a statistically significant sample of rare events. Detailed elemental and isotopic identification of nuclei requires that the particles' angle of incidence be measured—a major instrumental challenge.

To illustrate, one widely used technique for identifying nuclei is the $\Delta E/\Delta x$ vs. $E$ method. In this method, the energy loss ($\Delta E$) of an event is first measured. From the thickness of material the particle traversed ($\Delta x$), the energy loss rate ($\Delta E/\Delta x$) is determined. The residual energy ($E$) is measured by stopping the particle in one or more additional detectors. For events at an angle $\theta$ from the normal, $\Delta x$ goes as sec($\theta$). Variation in detector material traversed ($\Delta x$) by events with different angles of incidence can limit the charge and mass resolution. Position Sensing Detectors (PSD's) arranged into hodoscopes can determine the trajectory of individual events (e.g., Simpson et al., 1992) so the data can be corrected for angle of incidence. For example, using PSD's the High Energy Telescope on the *Ulysses* spacecraft measured the isotopes of Fe with a mass resolution of 0.28 amu (Connell and Simpson, 1997).

A large variety of position sensing detectors have been successfully employed in hodoscopes on spacecraft. Unfortunately, all of these systems add significant complexity and inevitably increase the number of electronic and pulse height channels. At a minimum, two 2-dimensional PSD's are required to determine a trajectory. The system that uses the least electronics channels has resistive charge divider chains for the strips on both sides of each detector (e.g. Anglin, Pyle and Simpson, 1990). This system thus requires three signal channels per detector (one end of one chain grounded) for a total of six signals, each with its own amplifier chain and pulse-height.

To overcome many of these problems, one of the authors (J. J. C.) has recently devised a new technique to determine the angle of incidence of particle events using simple (not position sensing) detectors: the Angle Determining Inclined Sensors (ADIS) system (Connell, Lopate and McKibben, 2001).

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## 2. The ADIS Concept

Fig. 1 shows the ADIS concept in its most basic form as applied to a *ΔE/Δx* vs. *E* particle telescope, though the concept is also applicable to other detector systems and particle identification techniques. The design in Fig. 1 is optimized for Solar energetic particles; depending upon the application, thicker detectors might be preferred. The top three detectors (D1, D2 and D3) are 50 µm thick fully depleted silicon detectors. D4 is a 1000 µm thick fully depleted silicon detector. Both D1 and D4 are standard 300 mm$^2$ circular detectors mounted normal to the telescope axis. D2 and D3 are both angled at 30$^o$ with respect to the horizontal, D2 with its normal in the x-z plane, and D3 with its normal in the y-z plane. These detectors are oval in shape to match the projected geometry of D1 to D4. While the D2 and D3 detectors are a custom cut for shape, they are otherwise standard silicon detectors. These detectors comprise the ADIS system. All four detectors are nested as closely as possible to maximize the telescope acceptance angle. Surrounding D1-4 is a scintillator cup viewed by a photomultiplier tube that excludes both side penetrating events and events that fail to stop in D4.

ADIS uses the variations in the thickness of detector material particles traverse to determine the angle of incidence. Let $\theta$ be the angle of incidence projected into the x-z plane. The signal in D1 is then proportional to sec($\theta$) while the signal from D2 is proportional to sec($\theta + \phi$) where $\phi$ is the D2 inclination. Assuming D1 and D2 are of the same thickness, for minimally ionizing particles,

$$\frac{E_1}{E_2} = \frac{\cos(\theta+\phi)}{\cos(\theta)} \tag{1}$$

where $\mathrm{E}_1$ and $\mathrm{E}_2$ are the energy signals from D1 and D2 respectively. θ can be found by inverting equation (1). The third detector (D3) inclined in the y-direction makes it possible to fully determine the angle of incidence.

Consider events stopping in D4. Define unit vectors $\hat{\boldsymbol{i}}$, $\hat{\boldsymbol{j}}$ and $\hat{\boldsymbol{k}}$, with $\hat{\boldsymbol{k}}$ along the central z-axis of the telescope. The orientations of the D1, D2 and D3 are defined by the normal unit vectors $\hat{\boldsymbol{n}}_{\boldsymbol{1}}$, $\hat{\boldsymbol{n}}_{\boldsymbol{2}}$ and $\hat{\boldsymbol{n}}_{\boldsymbol{3}}$. With inclinations of 30$^o$ from the horizontal for D2 and D3,

$$\hat{\boldsymbol{n}}_{\boldsymbol{1}} = \hat{\boldsymbol{k}} \tag{2}$$

$$\hat{\boldsymbol{n}}_{\boldsymbol{2}} = \frac{\sqrt{3}}{2}\hat{\boldsymbol{k}} + \frac{1}{2}\hat{\boldsymbol{i}} \tag{3}$$

$$\hat{\boldsymbol{n}}_{\boldsymbol{3}} = \frac{\sqrt{3}}{2}\hat{\boldsymbol{k}} + \frac{1}{2}\hat{\boldsymbol{j}} \tag{4}$$

The incident particle direction may be represented by a non-unit vector, $\boldsymbol{p}$, with components

$$\boldsymbol{p} = \hat{\boldsymbol{k}} + D_x\hat{\boldsymbol{i}} + D_y\hat{\boldsymbol{j}} \tag{5}$$

The cosines of the angles of incidence on each detector then can be found from the dot products:

$$\cos(\theta_1) = \frac{\boldsymbol{p}\bullet\hat{\boldsymbol{n}}_{\boldsymbol{1}}}{|\boldsymbol{p}|} = \frac{1}{\left(1+D_x^2+D_y^2\right)^{1/2}} \tag{6}$$

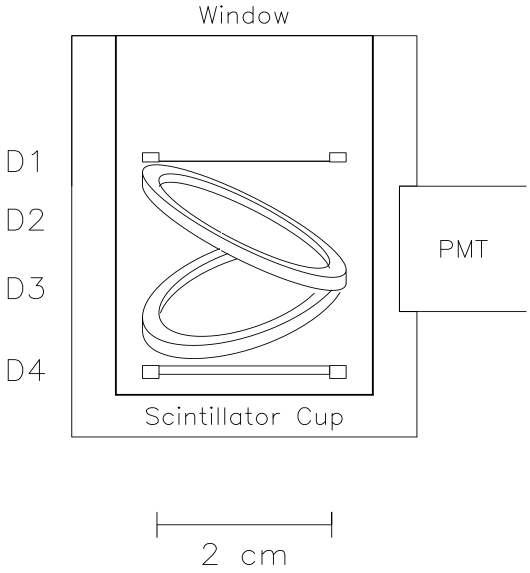

**Fig. 1.** Simple *ΔE/Δx* vs. *E* particle telescope demonstrating the ADIS concept. D1 and D4 are circular detectors mounted normal to the telescope axis. D2 and D3 are oval and angled at 30$^o$ with respect to the horizontal, D2 with its major axis along the x-direction, and D3 along the y-direction. A scintillator cup surrounds D1-4. Detector rings are also shown.

$$\cos(\theta_2) = \frac{\boldsymbol{p}\bullet\hat{\boldsymbol{n}}_{\boldsymbol{2}}}{|\boldsymbol{p}|} = \frac{1}{2}\frac{\sqrt{3}+D_x}{\left(1+D_x^2+D_y^2\right)^{1/2}} \tag{7}$$

$$\cos(\theta_3) = \frac{\boldsymbol{p}\bullet\hat{\boldsymbol{n}}_{\boldsymbol{3}}}{|\boldsymbol{p}|} = \frac{1}{2}\frac{\sqrt{3}+D_y}{\left(1+D_x^2+D_y^2\right)^{1/2}} \tag{8}$$

To determine the charge of nuclei, we will use the "ZCAL" method (Lau, 1985). The range (*R*) in matter of a heavy ion is approximated as a power law in energy per nucleon. Then, under the further approximation that *A* = *2Z*,

$$R = \kappa\frac{E^a}{Z^{a+1}} \tag{9}$$

where $\alpha$ and $\kappa$ are empirically determined constants. For events stopping in D4, one then obtains four equations. For example,

$$R_0 + T_3\sec(\theta_3) = \frac{k}{Z^{a+1}}\left(E_4+E_3\right)^a \tag{10}$$

where the *T*'s are the detector thicknesses, the *E*'s are the measured energy depositions in the detectors and $R_0$ is the (unknown) range in the stopping (D4) detector. Using equations (6-8) gives four independent equations in four unknowns that can be solved in closed form to give

$$D_x =$$

$$2\frac{T_2}{T_1}\left[\frac{\left(E_4+E_3+E_2+E_1\right)^a - \left(E_4+E_3+E_2\right)^a}{\left(E_4+E_3+E_2\right)^a - \left(E_4+E_3\right)^a}\right] - \sqrt{3} \tag{11}$$

$D_y =$

$$2\frac{T_3}{T_1}\left[\frac{\left(E_4+E_3+E_2+E_1\right)^a-\left(E_4+E_3+E_2\right)^a}{\left(E_4+E_3\right)^a-E_4^a}\right]-\sqrt{3} \qquad (12)$$

and

$\mathrm{Z} =$

$$\left[\frac{\kappa}{\mathrm{T}_1}\frac{\left(\mathrm{E}_4+\mathrm{E}_3+\mathrm{E}_2+\mathrm{E}_1\right)^{\alpha}-\left(\mathrm{E}_4+\mathrm{E}_3+\mathrm{E}_2\right)^{\alpha}}{\left(1+\mathrm{D}_x^2+\mathrm{D}_y^2\right)^{1/2}}\right]^{1/(\alpha+1)} \qquad (13)$$

Thus, from the signals in the four detectors, the angle of incidence and charge and, as will be seen in the next section, the mass of heavy ions is determined.

From the above the advantages of the ADIS system should be clear. From the simplest possible two detector $\Delta E/\Delta x$ vs. $E$ telescope, the ADIS gives trajectory determination with only the addition of two simple detector elements, amplifier chains and pulse height analysis channels. Furthermore, only modest computing power is needed to perform the analysis—no trigonometric functions are required. The full analysis can be performed with low-power on-board processors rather than requiring that pulse-height data be sent down for analysis as with most PSD's. With on-board processing event counts can be accumulated (by charge, mass, energy, etc.) with only the accumulated tables sent down, a major savings in telemetry.

## 3. Simulations of the ADIS Response

To test the instrument concept, we have made Monte-Carlo simulations of the telescope shown in Fig. 1. The well proven software used to design our instruments on the CRRES and *Ulysses* missions was modified to include inclined oval detectors and mounting rings. The simulations include reasonable estimates of structural ("dead") material in the telescope. The data thus generated was analyzed in a separate blind operation. The simulations shown were made assuming a power law spectrum with index of -3.0, which is fairly typical for SEP events at high energy.

To test events stopping in D4, we simulated data for the most abundant isotopes of H, He, C, N, O, Ne, Mg, Si, Cr, Mn, Fe, Co and Ni in approximately equal numbers. $^3$He and $^{22}$Ne were added at the 25% level. Fig. 2 shows the results. Plots A, B and C show the energy loss in D1 ($\Delta E/\Delta x$) as it would be with no correction for angle versus the residual energy (the sum of D2, D3 and D4). No noise was included in these simulations so the full effects of the differing angles of incidence are seen. These results are equivalent to those of a flat detector $\Delta E/\Delta x$ vs. $E$ instrument. Plots D, E and F show the exact same data using the ADIS measurement to correct for angle of incidence. The ADIS calculation was also used to select events with angles of incidence limited to less than 25$^{\circ}$—or more precisely, the secant squared of the angle was limited. This selectively reduces the number of events stopping in structural material, reducing the backtracks seen in plots A, B and C. The improvement due to ADIS is marked. The Fe-group elements that are now clearly resolved, as are the $^{20}$Ne and $^{22}$Ne tracks. Plots G, H and I show the charge found using the ZCAL with ADIS method. Individual elemental and isotopic peaks are seen for the full range of elements. The isotopic separation arises from perturbations from the $A = 2Z$ approximation used for ZCAL.

At the lowest energies, the ZCAL approximation begins to break down, in turn affecting the ADIS correction. The backtracks at higher energies result mainly from events stopping in structural material (e.g. detector rings or support struts). Any telescope using the ADIS system will need to minimize dead material in the telescope design.

The ADIS system also provides directional information that is of great use in anisotropy studies. Including detector noise, an angular resolution of ~4$^{\circ}$ for protons stopping in D4 is achieved in the above design.

## 4. Conclusions

Space based and balloon borne instruments to study Solar energetic particles, Galactic cosmic rays and anomalous cosmic rays are usually constrained by limited resources in terms of mass, power and telemetry. At the same time, large detector area and acceptance angle, together with good elemental and isotopic resolution, can be critical for the required measurements. High resolution particle identification requires that the angles of incidence of ion events be determined. Hodoscopes of position sensing detectors add significant complexity and require additional electronics, thus increasing both instrument mass and power usage. The Angle Detecting Inclined Sensor system overcomes many of these problems.

The ADIS makes use of geometry and the variation in detector response with the thickness of material traversed by nuclei. With essentially three simple detectors, and three electronics channels, the ADIS system can determine the angle of incidence, together with an energy loss measurement, of an ion. Thus, ADIS has a minimal impact on mass and power. The calculation of the angle of incidence, the charge and mass of an event in an ADIS instruments is well within the capabilities of on-board processors, thus making maximum use of available telemetry.

ADIS may also have applications for other charged particle measurements, such as in cosmic ray air shower arrays or accelerator experiments.

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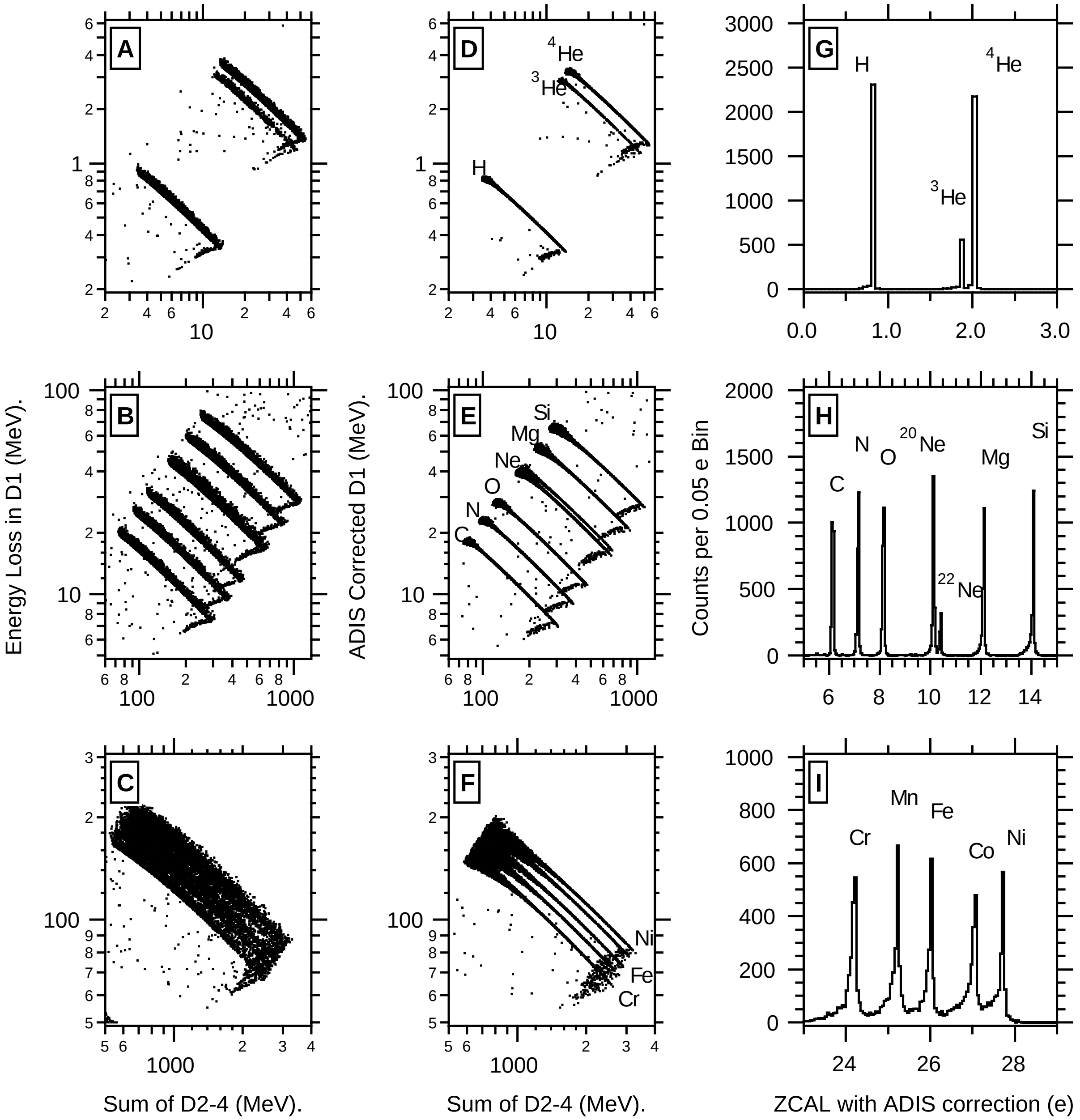

**Fig. 2.** ADIS Telescope response to H, He, C, N, O, Ne, Mg, Si, Cr, Mn, Fe, Co and Ni for events stopping in D4. (A), (B) and (C) are with no angle correction. (D), (E) and (F) are with ADIS angle correction. (H), (I) and (J) are ZCAL histograms with ADIS correction.

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