GeMini Plus: A Low Resource, High Precision Gamma-Ray Spectrometer for Planetary Composition Measurements. David J. Lawrence[1], Morgan T. Burks[2], John O. Goldsten[1], Patrick N. Peplowski[1], Andrew W. Beck[1], [1]Johns Hopkins University Applied Physics Laboratory (JHU/APL), Laurel, MD (David.J.Lawrence@jhuapl.edu), [2] Lawrence Livermore National Laboratory, Livermore, CA.

Introduction: Knowing the elemental composition of a planetary surface is key to understanding its formation and evolution. Planetary gamma-ray spectroscopy is a well-established technique for remotely measuring planetary elemental concentrations for the following elements: H, C, O, Na, Mg, Al, Si, S, Cl, K, Ca, Ti, Fe, Th, and U. It is unique among the available techniques in that it measures bulk concentrations to depths of tens of cm (in contrast to techniques sensitive only to the top tens of microns) and can quantify compositional layering within this range. Orbital gamma-ray measurements have resulted in significant discoveries from the Moon, Mars, Mercury, and asteroids. However, surface *in situ* gamma-ray spectroscopy has been relatively limited and not fully realized because the laboratory-quality spectrometers required for the most important measurements are not yet developed within the low resources (e.g., mass, power) needed for landed missions. Here we discuss a new instrument called GeMini Plus that can accomplish laboratory quality, high-precision gamma-ray measurements with the type of low-resources needed for landed platforms as well as resource-constrained orbital missions.

High-Precision Gamma-Ray Spectroscopy: The performance of gamma-ray spectrometers is characterized by two principal parameters: intrinsic energy resolution and sensor efficiency. Intrinsic energy resolution quantifies the ability of a GRS system to spectrally resolve energy-specific gamma-ray lines from nearby lines as well as to resolve these lines from background counts. Sensor efficiency quantifies the ability of a gamma-ray sensor to convert incident gamma rays into measurable counts. High-density and large-volume sensors provide more statistically significant measurements than low-density and small-volume sensors. Historically, planetary gamma-ray sensors have been either inorganic scintillators (NaI, CsI, BGO, LaBr) or cryogenically-cooled high purity Ge (HPGe) sensors. The energy resolution for scintillators is typically quoted as a percentage at 662 keV and has values ranging from 3 to 15%. In contrast, HPGe sensors have resolutions (typically quoted as a percentage at 1332 keV) of <0.5%. Fig. 1 illustrates the difference between the two types of sensors where gamma-ray spectra from HPGe and CsI sensors are shown. The superior energy resolution – or "laboratory quality performance" – of the HPGe sensor is clearly seen.

Because scintillator-based sensors are inherently easier to build and deploy, the first uses of planetary gamma-ray spectroscopy were accomplished using scintillators. For these measurements at the Moon [1,2] and the asteroid Eros [3,4], NaI, CsI, and BGO scintillators made compositional measurements that enabled significant new scientific insights to be obtained. While there continue to be applications where scintillators provide an optimum solution [5], many important planetary compositional measurements require a high-precision gamma-ray spectrometer. HPGe gamma-ray measurements have been made at Mars, the Moon, and Mercury [6-8].

A case study of MESSENGER GRS data illustrates the ability of the HPGe sensors to make measurements not possible with scintillators. Fig. 2 shows the energy range around 2.2 MeV where many overlapping peaks are found, including important signatures from Al, S, and H, none of which are separable in a scintillator

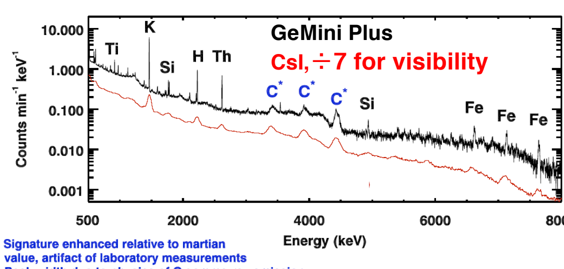

Fig. 1. Measured gamma-ray spectra for the GeMini Plus HPGe spectrometer and a CsI-based gamma-ray spectrometer of Mars soil simulant at the JHU/APL Planetary Gamma-Ray and Neutron Simulation Facility.

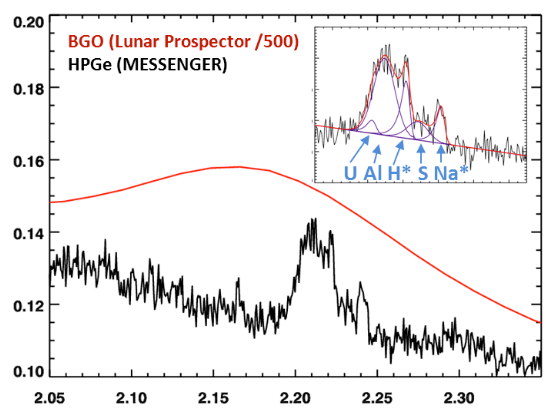

Fig. 2. MESSENGER GRS measurements at Mercury (black) and equivalent measurements with a BGO scintillator (red). Inset shows how the contributions from various gamma-ray lines are separated with the narrow HPGe energy resolution.

spectrum. However, with the MESSENGER GRS, the contribution from each line was quantified, which enabled the measurement of Al and S concentrations on Mercury's surface [9].

A major drawback of current space-based HPGe systems is their relatively large mass and power requirements (>10 kg, >16 W), which are increasingly incompatible with future resource-constrained planetary missions, especially surface-based landers and rovers (Table 1). As a consequence, laboratory-quality gamma-ray spectroscopy has not been been a viable option for such missions. To address this need and to provide revolutionary, high-quality compositional measurements, we have developed a new low-resource, HPGe spectrometer that will obtain the same type of laboratory-quality measurements that to date have only been obtained using significantly larger-resource instruments.

Table 1. Resource parameters for selected HPGe GRS systems.

	Mars Odyssey (MO) GRS	**MESSENGER GRS**	**GeMini Plus**
Mass	30.2 kg[a]	9.2 kg	<3 kg
Power	30 W[a]	16.5 W	<11 W
Energy Resolution[b]	3.6 keV (Launch) 4.8 keV (Orbit)	3.5 keV (Launch) 4.4 keV (Orbit)	<3 keV

[a]Mass/power given for entire MO GRS instrument suite, which included two neutron spectrometers
[b]Energy resolution quoted for standard reference line at 1332 keV.

GeMini Plus Gamma-Ray Spectrometer: The same team at Lawrence Livermore National Laboratory (LLNL) that helped design and build the MESSENGER GRS has since designed a miniature HPGe (GeMini) detector (Fig. 3) for use in national security applications [10]. These applications require a lightweight, small, low-power instrument, which are exactly the same demands required of instruments for planetary science missions. At the heart of GeMini is a coaxial HPGe sensor which, when cooled to 90 K during operation, provides laboratory-quality energy resolution. It has a beveled cylindrical shape (5 × 5 cm), and is suspended by Kevlar strings within a vacuum cryostat to achieve thermal isolation. GeMini uses the same crystal size and shape as the MESSENGER GRS [11] and so achieves the same sensitivity. GeMini does not use a plastic scintillator anticoincidence shield (ACS) as was used on MESSENGER because the background reduction provided by an ACS is not needed for surface-based measurements. However, if active background rejection is needed, an ACS can be added at the cost of extra mass and power.

The GeMini instrument is the starting point for the development of GeMini Plus, which is the planetary science version of GeMini. A third-generation GeMini has been tested in at APL's Planetary Gamma-ray and Neutron Simulation Facility to assess its readiness for planetary applications. Activities included a demonstration of GeMini operation with MESSENGER flight electronics, (Fig. 3), testing in a thermal chamber, and demonstrating GeMini's ruggedness by conducting

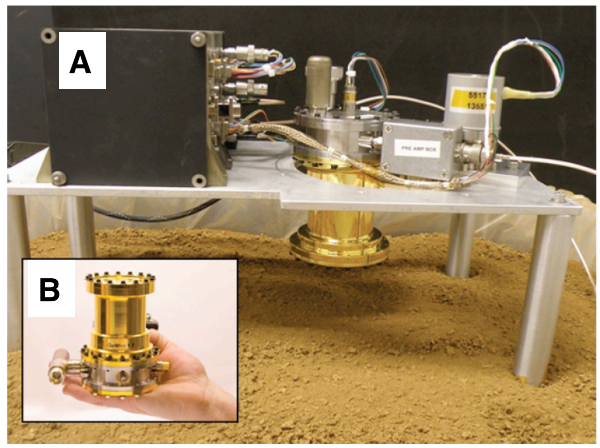

Fig. 3. (A) GeMini sensor operating with MESSENGER GRS flight electronics at the JHU/APL Planetary Gamma-Ray and Neutron Simulation Facility. The full instrument is placed on top of a container of Mars soil simulant and is measuring gamma-rays produced by an AmBe neutron source placed within a pile of reactor-grade graphite [12] This graphite moderates the neutrons to achieve a neutron spectrum that is similar to a planetary neutron flux spectra, which in turn produces gamma-ray flux spectra similar to what is measured on a planetary surface. (B) Inset shows relative size of the GeMini sensor.

launch-like vibration tests with no failures. GeMini measured gamma-ray lines from Mars soil simulants and iron meteorites (Figs. 1 and 4). The measured energy resolution (0.3% at 1332 keV and 0.5% at 662 keV) exceeds the performance of the MESSENGER GRS. When combined with the next generation MESSENGER-type GRS electronics, the GeMini Plus mass and power usage are <3 kg and <11 W (Table 1). MESSENGER-based measurements, laboratory tests, and particle transport simulations show that surface-based elemental concentration measurements can be accomplished at <5% accuracy within 12 to 24 hours using the GeMini Plus sensor.

Example Surface Application: Elemental Stratigraphy Measurements: A surface-based GRS can make important and revolutionary new compositional measurements for many types of missions (e.g., lunar

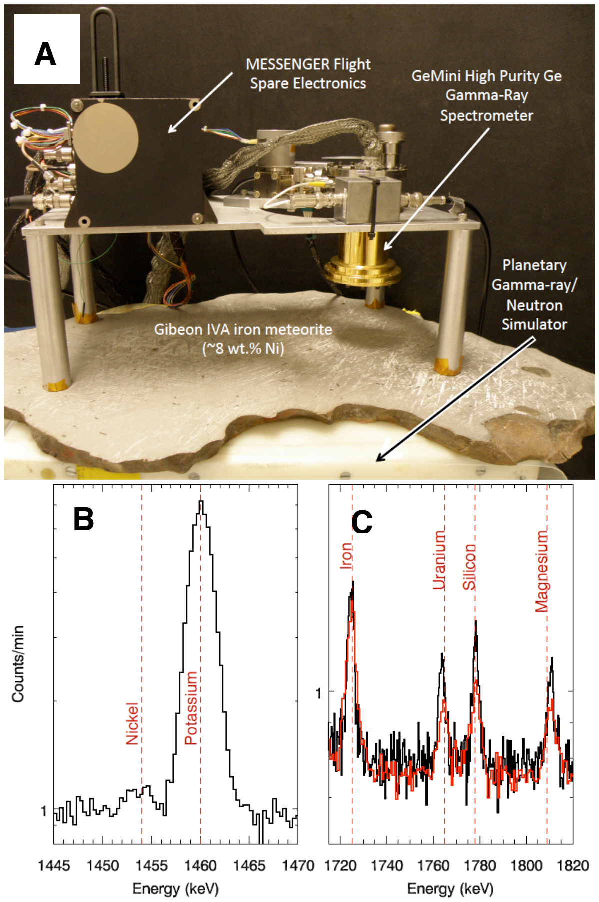

Fig. 4. (A) GeMini sensor measuring planetary-like gamma-rays from the IVA iron meteorite Gibeon, which has 8 wt.% Ni. (B) Measured gamma-ray spectra from Gibeon in the energy region of K and Ni gamma-ray lines. The high energy resolution of the HPGe sensor allows the K and Ni lines to be separated, enabling a quantification of the meteorite's Ni concentration. The large K count rate is due mostly room background and does not originate from the meteorite. (C) Comparison of gamma-ray spectra from the Gibeon (red) and the IAB iron meteorites Campo del Cielo (black) in the region containing Si and Mg. The gamma-ray data agree with prior knowledge that Campo del Cielo has larger Si and Mg concentration [13].

polar hydrogen deposits, comet suface sample return, Mars surface). To illustrate, one new type of measurement that is enabled by a surface-based HPGe sensor is measuring the elemental concentration of buried materials to depths of tens of cm. This technique would not only provide a new type of science measurement, but provide strategic information for missions seeking to identify high-value materials that are buried under a few cm of less strategically useful material.

This technique to quantify the elemental concentration of buried materials leverages a basic property of gamma-ray transport that the mean attenuation length varies with the energy of the gamma-ray emission (Fig. 5). Since most elements have multiple gamma-ray emissions, each with its own attenuation length, HPGe measurements provide a unique and powerful tool for measuring depth-dependent elemental variability. Terrestrial field tests have demonstrated that burial depths of naturally radioactive rock and soil layers containing Th and U can be measured to a precision better than 30% [14]. Those field tests required an HPGe sensor to resolve the necessary lines.

Laboratory tests have shown that ratios of high- to low-energy Si gamma-ray count rates can measure the depth to a silica layer buried under a Mars soil simulant (Fig. 6). This is a scenario that simulates the type of buried silica deposits discovered by the Sprit rover [15]. Similar measurements can be made for any element with multiple gamma-ray signatures such as Al, S, Cl, Ca, Ti, Fe, Th, and U. Simulations for multiple elements show that a precision of 2 cm for deposit burial depths up to 20 cm is achievable in <24 hrs.

Summary: GeMini Plus is a low-resource, highly developed gamma-ray spectrometer that can bring laboratory-quality gamma-ray measurements to a planetary surface for the first time. Its use on planetary surfaces where compositional layering is known or expected to occur (e.g., Mars, comets, polar permanently shaded regions) will provide a new and unique type of measurement that will enable significant scientific discoveries.

References: [1] Metzger, A. E., et al. (1977), *Proc. 8th Lunar Sci. Conf.*, 949; [2] Lawrence, D. J. et al. (1998), *Science*, 281, 1484; [3] Evans, L. G., et al. (2001), *Met. and Planet. Sci.*, 36, 1639; [4] Peplowski, P. N. et al. (2014), *NASA SSERVI ESF*; [5] Peplowski, P. N., et al. (2014), *International Workshop on Instrumentation for Planetary Missions*; [6] Boynton, W. V., et al. (2002), *Science*, 297, 10.1126/ science.1073722; [7] Hasebe, N. et al. (2007), *Earth Planets and Space*, 60, 312; [8] Peplowski, P. N. et al. (2011), *Science*, 333, 1850; [9] Evans, L. G., et al. (2012), *JGR*, 10.1029/2012 JE004178; [10] Burks, M. (2008), *IEEE Nuc. Sci. Symp.*, 1375; [11] Goldsten, J. O., et al. (2007), *Space Sci. Rev.*, 10.1007/s11214-007-9262-7; [12] Feldman, W. C., et al (1995), *Nuc. Inst. and Methods A*, 362, 561, 10.1016/0168-9002(95)00287-7. [13] Ruzicka, A., (2014), *Chemie der Erde*, 74, 3, 10.1016/j.chemer.2013.10.001; [14] Thummerer, S., and P. Jacob (1998), *Nucl. Inst. Meth. A*, 416, 161, 10.1016/S0168- 9002(98)00636-6; [15] Squyres, S. W., et al. (2008), *Science*, 320, 10.1126/science. 1155429.

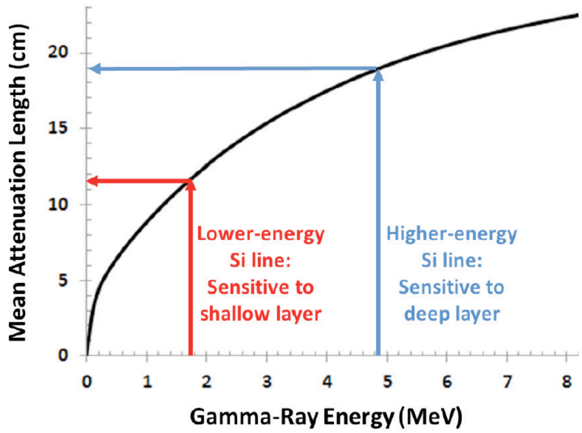

Fig. 5. Buried layer depths are measured by multiple gamma rays. Two Si gamma rays (1.779 and 4.934 MeV) have different attenuation lengths and are sensitive to material from shallow and deep layers. The same technique can be applied to many other elements.

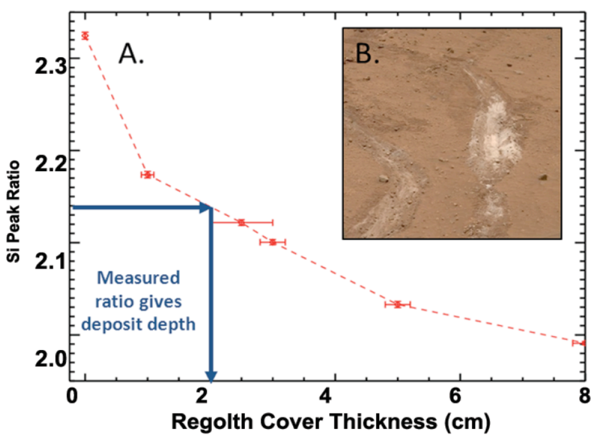

Fig. 6. Laboratory measurements of Si gamma-ray emission as a function of the burial depth of a Si-rich deposit confirm that photon ratios are a sensitive measure of burial depth. In this case, the ratio of the 1778- to 4934-keV photons, which sample mean depths of ~12 and ~19 cm, respectively (Fig. 5), track closely with the burial depth of pure SiO_2, a stand-in for opaline-rich material such as that found by the Spirit rover in Gusev crater (B) [15].