Application of Hyperspectral PRISMA data: from CO_2 and CH_4 retrieval to the future perspective in Hazard Assessment

Introduction and State of Art

The release into the atmosphere of greenhouse gases (e.g., carbon dioxide, methane), deriving from both natural phenomena and human activities, are decisive for the global warming trend in recent decades (Masson-Delmotte et al., 2018; 2021).

It is important to better understand the processes controlling changes in atmospheric methane (CH_4) and carbon dioxide (CO_2), the two dominant anthropogenic climate-forcing agents. CH_4 and CO_2 contribute approximately 17 and 64 % of the total radiative forcing attributed to anthropogenic greenhouse gases. Although CH_4 has a short atmospheric lifetime (about 9 years), it has a very high global warming potential that is 86 times greater than CO_2 on a 20-year timescale (Myhre et al., 2013). This means that even small amounts of emissions reduction will result in large reductions in the overall atmospheric radiative forcing (Thorpe et al., 2017).

In volcanic systems, the passive release of fluids from hydrothermal and magmatic sources marks the inter-eruptive periods. The diffuse soil degassing activity can generate gas hazard, asphyxiation, or poisoning, allowing the accumulation of harmful gases, especially under low wind conditions or in depressed areas. In addition, attention is focused on the long-term (active and passive) release which may affect human health and may increase the knowledge in terms of forecasting. Critical gas hazard conditions occur in volcanic areas: large plumes, weakly degassing sites, fumarolic fields, mud volcanoes, and they can occur also in other geological systems on Earth. The volcanic/hydrothermal CO_2 flux sustained by diffuse soil degassing can be measured relatively easily during ground-based surveys or permanent installations (Pedone et al., 2014, and references therein).

In contrast, the volcanic CO_2 flux contributed by open vents and fumarolic fields is more difficult to measure, since the volcanic CO_2 gas signal is diluted – upon atmospheric transport – into the background air CO_2 signal. Such volcanic CO_2 flux emissions have been quantified for only ∼ 30 volcanic sources, based upon simultaneous measurement of SO_2 fluxes (via UV spectroscopy) and proximal/in situ CO_2/SO_2 plume ratios. This methodology is however not applicable to the countless number of quiescent volcanoes with low temperature (and SO_2-free) emissions (Pedone et al., 2014; 2017). As a consequence, the available dataset of volcanic CO_2 fluxes is still incomplete, making estimates of the global volcanic CO_2 flux inaccurate (Burton et al., 2013). Pedone et al. (2014) have proposed a methodology to extrapolate CO_2 flux from ground-based instruments. Moreover, they have suggested that ∼ 500 volcanoes have a CO_2 flux higher than $10\ t{\cdot}d^{-1}$ and they have extrapolated a global CO_2 flux of $67\ Mt{\cdot}yr^{-1}$. The methodology was then refined by using the (Lagrangian and Eulerian) modelling of gas dispersion into the atmosphere (Pedone et al., 2017).

As regards the utilization of satellite-based acquisitions, few tests were carried out to discriminate volcanic emissions from the surface deposits (Licciardi et al., 2017) or to determine the chemical composition of the plumes. The column-averaged dry-air mole fraction of CO_2 (XCO_2) is currently measured by several satellite sensors such as TANSO-FTS on board the GOSAT satellite (from 2009) (Kuze et al., 2009), OCO-2 (from 2014) (Schwandneret et al., 2017), TanSAT (from 2016) (Yang et al., 2018) and OCO-3 on board the ISS (from 2019) (Eldering et al., 2019).

However, high spatial resolution instruments can identify and retrieve the punctual emissions (like volcanoes) of carbon dioxide and methane. By combining spectral analysis and the atmospheric dynamics modelling, measurements of point sources emissions (natural or anthropogenic) are possible; PRISMA, with its high spatial resolution, as described below, is suitable for this purpose.

Very recently, an application of absorbing spectral channels by using satellite datasets allowed the measurement of CO_2 column contents (Romaniello et al., 2021). In detail, gas concentrations can be retrieved from spectra in the CO_2 absorption bands around 1.6 µm and 2.0 µm in the short-wave infrared (SWIR) spectral region, at 4.8 µm in the mid-wave infrared region (MWIR), and at 15 µm in the thermal infrared region (TIR). The CO_2 absorption bands in the MWIR spectral region have been little studied in the literature; and it seems suitable only on surfaces characterized by high temperatures (i.e., on fires and lava flows) (Romaniello et al., 2020). To date, these bands have not been exploited in the operative satellite missions but are only experienced through airborne sensors (i.e., MASTER, Hook et al., 2001).

Carbon dioxide absorption bands in the SWIR spectral range are sensitive down to the lowermost layers of the atmosphere, which are particularly affected by fluxes emitted from point sources.

Methane absorption bands are ranged between 2.3-2.4 µm; quantitative retrieval of methane was made by airborne imaging spectrometers like the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS, Spinetti et al., 2008; Carrere and Conel, 1993) and the next-generation instrument AVIRIS-NG (Mishra et al., 2019) that can map large regions (Thorpe et al., 2017).

ASI-PRISMA mission and PRISMA-based application

The Italian Space Agency launched a hyperspectral imaging platform (PRecursore IperSpettrale della Missione Applicativa, PRISMA) on 22 March 2019 (Loizzo et al., 2018). PRISMA holds a panchromatic camera, acquiring images at 5 m spatial resolution, and a hyperspectral payload. The hyperspectral camera works in the range of 0.4–2.5 µm (a range which includes both CO_2 and CH_4 absorption features) with 66 and 173 channels in the VNIR (visible and near infrared) and SWIR (short-wave infrared) regions, respectively, and has a spatial resolution of 30 m.

Several studies employing PRISMA data have been carried out for specific applications (Giardino et al., 2020; Casa et al., 2020) and the radiometric performance was also evaluated (Romaniello et al., 2020b). Recent works used PRISMA data, in the SWIR spectral range, for achieving enhancements of XCO_2 (and XCH_4) around large point sources such as power plants and gas well blowouts (Romaniello et al., 2021, and references therein). In a previous study by Romaniello et al. (2021) a methodology based on the CIBR (Continuum Interpolated Band Ratio) technique was developed and arranged on PRISMA data with the aim of estimating XCO_2 enhancements on natural sources such as mud volcanoes and fumaroles. The CIBR technique is used to analyse the spectral CO_2 absorptions and to quantify gas concentrations in the atmosphere and in volcanic plumes; this technique was previously applied to hyperspectral data collected by AVIRIS (Airborne Visible/InfraRed Imaging Spectrometer) (Spinetti et al., 2008; Carrere and Conel, 1993) and AVIRIS-NG (Next Generation) sensors (Mishra et al., 2019). The methodology, described by Romaniello et al., (2020), is applied to two test cases in different regions: the LUSI volcanic area (Indonesia) and the Solfatara area in the caldera of Campi Flegrei (Italy). The method seems to be able to retrieve CO_2 enhancements from different gas sources with a minimum detectable XCO_2 value, above the background, of about 40 ppm. The methodology can be applied, with satisfactory success, for medium/strong emissions and over soils with a reflectance greater than 0.1.

By using other methodologies, the retrieval column XCO_2 and XCH_4 was achieved by applying the Iterative Maximum A Posteriori-Differential Optical Absorption Spectroscopy (IMAP-DOAS) algorithm (Cusworth et al., 2021, 2019; Thorpe et al., 2017).

To date, few PRISMA applications are in the field of the study of atmospheric compositions and dynamics from point sources. Furthermore, the potential of PRISMA acquisitions has not yet been exploited to:

- find precursors of medium/large gas emission events by remote sensing from space;
- identify some kinds of cyclical properties in natural gas emissions phenomena.

Aim of the project

Starting from the state of art and the few applications above summarized, the project is aimed to explore the possibility to use PRISMA datasets to improve:

- the methodologies and the algorithms to estimate point sources emissions of carbon dioxide and methane;
- the characterization of gases emissions with particular regards to volcanic-like emissions;
- the extrapolation of global budget estimates starting from the punctual emissions;
- the possibility to achieve new precursors of hazardous events directly from the space-based acquisitions;
- the numerical modelling of atmospheric dynamics;
- the capability to find and monitor cyclical phenomena in carbon dioxide and methane degassing;
- the forecast from space;
- the refinement of the next hyperspectral ASI PRISMA-like missions.

Details of the project

ASI Supervisors:

- Maria Pedone (UCR):
- Paola Manzari (UCR);
- Giorgio Antonio Licciardi (UDS).

Suggested Collaborations:

With the aim to compare the analysis of hyperspectral and multispectral data acquired by remote sensing techniques with the ground-based chemical-physical measurements, a collaboration with INGV (Istituto Nazionale di Geofisica e Vulcanologia) would be desirable.

In fact, in this case, gas/plume compositions and fluxes deriving from both in situ and remote sensing data could be readily compared in a specific case of study.

INGV collaborators: Maria Fabrizia Buongiorno, Vito Romaniello

Duration: 24 months.

References

Burton, M. R., Sawyer, G. M., and Granieri, D., Deep Carbon Emissions from Volcanoes, 2013, Rev. Mineral. Geochem., 75, 323–354.

Carrere, V., Conel, J.E., Recovery of atmospheric water vapor total column abundance from imaging spectrometer data around 940 nm—Sensitivity analysis and application to airborne visible/infrared imaging spectrometer (AVIRIS) data, 1993, Remote Sens. Environ., 44, 179–204.

Casa, R., Pignatti, S., Pascucci, S., Ionca, V., Mzid, N., Veretelnikova, I., Assessment of PRISMA imaging spectrometer data for the estimation of topsoil properties of agronomic interest at the field scale. In Proceedings of the 22nd EGU General Assembly Conference, 2020, p. 6728.

Cusworth, D. H., Duren, R. M., Thorpe, A. K., Pandey, S., Maasakkers, J. D., Aben, I., et al. Multisatellite imaging of a gas well blowout enables quantification of total methane emissions, 2021, Geophysical Research Letters, 48, e2020GL090864, https://doi. org/10.1029/2020GL090864.

Cusworth, D. H., Jacob, D. J., Varon, D. J., Chan Miller, C., Liu, X., Chance, K., et al., Potential of next-generation imaging spectrometers to detect and quantify methane point sources from space, 2019, Atmospheric Measurement Techniques, 12, 5655–5668, https://doi. org/10.5194/amt-12-5655-2019.

Eldering, A., Taylor, T.E., O'Dell, C.W., Pavlick, R., The OCO-3 mission: Measurement objectives and expected performance based on 1 year of simulated data, 2019, Atmos. Meas. Tech., 12, 2341–2370.

Giardino, C., Bresciani, M., Braga, F., Fabbretto, A., Ghirardi, N., Pepe, M., Gianinetto, M., Colombo, R., Cogliati, S., Ghebrehiwot, S., et al. First Evaluation of PRISMA Level 1 Data for Water Applications, 2020, Sensors, 20, 4553.

Hook, S.J., Myers, J.J., Thome, K.J., Fitzgerald, M., Kahle, A.B., The MODIS/ASTER airborne simulator (MASTER)—A new instrument for earth science studies, 2001, Remote Sens. Environ., 76, 93–102.

Kuze, A., Suto, H., Nakajima, M., Hamazaki, T., Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gases monitoring, 2009, Appl. Opt., 48, 6716–6733.

Licciardi, G. A., Sellitto, P., Piscini, A., Chanussot, J., Nonlinear Spectral Unmixing for the Characterisation of Volcanic Surface Deposit and Airborne Plumes from Remote Sensing Imagery, 2017, Geosciences, 7, 46, doi:10.3390/geosciences7030046.

Loizzo, R., Guarini, R., Longo, F., Scopa, T., Formaro, R., Facchinetti, C., Varacalli, G, Prisma: The Italian Hyperspectral Mission. In Proceedings of the IGARSS 2018 IEEE International Geoscience and Remote Sensing Symposium, pp. 175–178.

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, C., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al., IPCC, 2021: Summary for Policymakers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al., IPCC, 2018: Summary for Policymakers. In Global Warming of 1.5 ◦C. An IPCC Special Report on the Impacts of Global Warming of 1.5 ◦C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of

Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty; World Meteorological Organization: Geneva, Switzerland, 2018, p. 32.

Mishra, M.K., Gupta, A., John, J., Shukla, B.P., Dennison, P., Srivastava, S.S., Dhar, D., Kaushik, N.K., Misra, A., Retrieval of atmospheric parameters and data-processing algorithms for AVIRIS-NG Indian campaign data, 2019, Curr. Sci., 116, 1–12.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H., Anthropogenic and natural radiative forcing, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013, Tech. rep., Intergovernmental Panel on Climate Change, 423, 658–740.

Pedone, M., Granieri, D., Moretti, R., Fedele A., Troise, C., Somma R., De Natele, G., Improved quantification of CO_2 emission at Campi Flegrei by combined Lagrangian Stochastic and Eulerian dispersion modelling, 2017, Atmospheric Environment, https://doi.org/10.1016/j.atmosenv.2017.09.033.

Pedone, M., Aiuppa, A., Giudice, G., Grassa, F., Francofonte, V., Bergsson, B., Ilyinskaya, E., Tunable diode laser measurements of hydrothermal/volcanic CO_2 and implications for the global CO_2 budget, 2014, Solid Earth, doi:10.5194/se-5-1209-2014.

Romaniello, V., Spinetti, C., Silvestri, M., Buongiorno, M.F., A Methodology for CO_2 Retrieval Applied to Hyperspectral PRISMA Data, 2021, Remote Sens., 13, 4502, https://doi.org/10.3390/rs13224502.

Romaniello, V., Spinetti, C., Silvestri, M., Buongiorno, M.F., A Sensitivity Study of the 4.8 µm Carbon Dioxide Absorption Band in the MWIR Spectral Range, 2020a, Remote Sens., 12, 172.

Romaniello, V., Silvestri, M., Buongiorno, M.F., Musacchio, M, Comparison of PRISMA Data with Model Simulations, Hyperion Reflectance and Field Spectrometer Measurements on 'Piano delle Concazze' (Mt. Etna, Italy), 2020b, Sensors, 20, 7224.

Schwandneret, F.M., Gunson, M.R., Miller, C.E., Carn, S.A., Eldering, A., Krings, T., Verhulst, K.R., Schimel, D.S., Nguyen, H.M., Crisp, D., et al., Spaceborne detection of localized carbon dioxide sources, 2017, Science, 358, eaam5782.

Spinetti, C., Carrere, V., Buongiorno, M.F., Sutton, A.J., Elias, T., Carbon Dioxide of Kilauea Volcanic Plume Retrieved by Means of Airborne Hyperspectral Remote Sensing, 2008, Remote Sens. Environ., 112, 3192–3199.

Thorpe, A. K., Frankenberg, C., Thompson, D. R., Duren, R. M., Aubrey, A. D., Bue, B. D., et al., Airborne DOAS retrievals of methane, carbon dioxide, and water vapor concentrations at high spatial resolution: Application to AVIRIS-NG, 2017, Atmospheric Measurement Techniques, 10, 3833–3850, https://doi.org/10.5194/amt-10-3833-2017.

Yang, D., Liu, Y., Cai, Z., Chen, X., Yao, L., Lu, D., First Global Carbon Dioxide Maps Produced from TanSat Measurements, 2018, Adv. Atmos. Sci., 35, 621.