International Academy of Astronautics Latin American Conference on Small Satellite Technologies and Applications

November, 4th to 9th - 2024
Salta, Argentina.

IAA • INTERNATIONAL ACADEMY OF ASTRONAUTICS

Secretaría de
Ciencia y Tecnología

**Ministerio de
Educación, Cultura,
Ciencia y Tecnología**

SALTA
GOBIERNO

IAA Latin American Conference on Small Satellite Technologies and Applications.

Proceedings of the International Academy of Astronautics Latin American Conference on Small Satellite Technologies and Applications

International Academy of Astronautics, 2024.

360 pages.

ISBN 978-2-917761-85-4

1st edition, November 2024.

IAA

6 rue Galilee.

75116 Paris, France

office@iaamail.org

https://iaaweb.org/

Design of the book & the cover: Secretaría de Ciencia y Tecnología.

secytec@edusalta.gov.ar

9 782917 761854

SAR Remote Sensing for rapid landslide detection in Latin America and the Caribbean

C. Paola Cardozo (1), Alessandro C. Mondini (2)

(1) Laboratorio de Teledetección y SIG. Instituto de Investigaciones en Energía no Convencional (INENCO-CONICET). Universidad Nacional de Salta (UNSa), Salta, Argentina. E-mail: paola.cardozo@conicet.gov.ar
(2) Istituto di Matematica Applicata e Tecnologie Informatiche "Enrico Magenes" Consiglio Nazionale delle Ricerche (IMATI-CNR). Genova, Italia.
E-mail: alessandro.mondini@ge.imati.cnr.it

Abstract: For rapid assessment during and after a disaster, we need a system that can penetrate clouds, such as synthetic aperture radar (SAR), which operates in the microwave spectral range where clouds are almost transparent. SAR measures both amplitude and phase. SAR amplitude depends on the type of backscatter, and landslides may backscatter differently from other land cover types, or changes in backscatter caused by the occurrence of a landslide may aid in their identification. This paper examines the current state of the art in exploiting SAR amplitude for new rapid landslide detection and its use in Latin America and the Caribbean (LAC). In this regard, the paper highlights the lack of LAC authors, and a limited investigation in the LAC areas compared to other areas of the world. In conclusion, radar imagery is suitable for mapping different types and sizes of rapid landslides in different physiographic settings, helping to reduce landslide risk, but is not fully exploited in certain areas of the world

1. INTRODUCTION

Remote sensing has entered a new era of artificial intelligence and big data. With the unprecedented availability of free remotely sensed data, tools, and computing platforms, increasingly sophisticated machine and deep learning-based models can be prepared for early mapping and hazard assessment including landslides, fires, floods, and volcanic eruptions. Landslides are a ubiquitous hazard in terrestrial environments [1, 2]; studying landslides worldwide is crucial for understanding the risks they pose to communities, infrastructure, and ecosystems. The data show that at least 55,997 people were killed in 4862 landslide events from 2004 to 2016 [3]. By analyzing their causes and patterns, we can improve early warning systems, mitigate their impacts, and develop strategies to prevent future disasters in vulnerable areas [4].

The spatial distribution of landslides reported by the different global databases is heterogeneous [5]. Countries that appear mostly in the top positions of the DesInventar and EM-DAT databases tend to be Latin American countries (e.g. Colombia, Chile, Perú, Haití, Honduras, Nicaragua, Guatemala, El Salvador), while in the GFLD and GLC databases, they tend to be Asian countries (e.g. Nepal, Taiwan, Afghanistan, the Philippines, Sri Lanka) [5]. Landslides in Latin America and the Caribbean (LAC) are frequent, abundant, and destructive [6, 7], so they should be monitored.

Systematic landslide detection and mapping are essential for identifying high-risk areas, guiding land use planning, and informing disaster response efforts, ultimately reducing the potential loss of life and property. Landslide mapping has traditionally been carried out by interpreting optical imagery and Digital

Elevation Models (DEM) and, particularly in the case of rapid detection, using machine learning applied to satellite optical imagery [4]. The presence of clouds hampers the possibility of mapping rainfall-induced landslides during or just after an event using optical imagery, which limits the information that can be provided to civil protection agencies [1]. Several examples show worldwide cases in which the first optical image after a landslide disaster is made available after months. For a rapid during and post-disaster assessment, we need a system that can penetrate clouds, such as a synthetic aperture radar (SAR) operating in the microwave spectral range where clouds are almost transparent [1]. SAR measures two quantities: amplitude and phase. SAR amplitude depends on the type of backscatter and landslides may backscatter differently from other land cover types, or changes in backscatter caused by the occurrence of a landslide can support their identification [1].

Considering that several landslide events have already occurred in LAC and are expected to increase [6], this paper examines the current state of the art in exploiting SAR amplitude for new rapid landslide detection and its use in LAC. We also analyzed triggering factors, types of landslides, types of SAR, and techniques used.

2. DETECTION AND MAPPING OF LANDSLIDE FAILURES USING SAR TECHNOLOGY

A SAR satellite illuminates the Earth's surface with coherent electromagnetic radiation in the microwave spectral range between 0.23 GHz (130 cm, P-band) and 40 GHz (0.65 cm, Ka-band) and records the phase and amplitude of the returning signal (i.e. the "echo") [1]. The difference in phase between two images taken over the same area at different times can be used to detect surface movement [e.g. 8]. Amplitude records the strength of the backscattered signal. SAR backscatter strength depends on several factors, including the signal source, the dielectric constant of the backscatterer, its roughness, and local orientation. Backscatter and its variations can detect changes in land cover caused by rapid landslides [1].

Qualitative and quantitative methods are used to detect landslide failures. Qualitative methods involve the visual interpretation of SAR images and derived products. Landslides can be read in the images in terms of tone discontinuities, textures, patterns, speckles, and grains and/or their changes [9]. Quantitative methods include statistical techniques and threshold methods and, more recently, are mostly based on machine and deep learning [1, 10, 11, 12, 13, 14]. Very promising seems to be the use of Deep Learning, in particular, Convolutional Neural Networks (CNN) to detect the occurrence of new landslides using worldwide temporal sequences of SAR Sentinel 1 image in the free computing platform Google Earth Engine and similar [e.g. 12].

3. DATA AND METHODS

In this paper, we extend the analysis of the state of the art carried out by [1] by adding an analysis of papers published between 2020 and 2024, with a greater emphasis on studies carried out in LAC and by LAC researchers, in particular on the use of SAR amplitude for landslide detection. We analyzed papers not only in English, as is traditionally done in reviews, but also papers in Spanish and Portuguese. Furthermore, the search was based on papers from high-impact journals and Latin American journals, in which many LAC researchers usually publish. We followed the same search criteria stated by [1] to complement the literature database. We also analyzed triggering factors, types of landslides, types of SAR and techniques used.

4. RESULTS

We analyzed one hundred papers and found seventeen new suitable papers, with most of them dealing with interferometry and then typically for monitoring slow-moving, deep-seated landslides and then not ideal for detecting fast events. Data shows that seventy-five new study areas are considered, forty in Asia (about 53.3%) [8,9,10,11,12,13,14,15,16,17,18,19,20], nine (12.0%) in LAC [12,14,16,21] and in Europe [16,22,23], seven (about 9.3%) in Oceania [10,11,12,16] and Africa [8,12,16], and three (4%) in North America [16] (Fig. 1). LAC countries include Brazil (two studies) [14, 16], Ecuador [16], Perú [16], Haití [12], Costa Rica [12], Colombia [12], Bolivia [21], and Chile [9] (one study each). Regarding to the triggering factors, in five studies landslides were triggered by rainfall (Ecuador, Brazil twice, Bolivia, and Chile) [9,14,16,21], in three by earthquakes (Haití, Costa Rica, and Colombia) [12], and in one case (Perú) [16] it is unknown. According to the respective authors, in two cases (Ecuador and Brazil) [14,16] landslides are classified as earth flows, in one case (Perú) [16] as debris flow, in one case as "mega-landslide" (Bolivia) [21], in one case as deep-seated landslide (Brazil) [14], in one case as rock slide (Chile) [9] and three cases as multiple unspecified events (Haití, Costa Rica and Colombia) [16]. Notably, LAC studies are only present in global studies, but in [21] the exploitation of SAR amplitude information in landslide mapping is just one of the purposes of the work.

Thirteen papers [8,9,10,11,12,13,14,16,18,19,21,22,24] use C-band Sentinel-1 imagery, one paper [17] uses C-band ENVISAT imagery, two [15,20] use L-band ALOS-2 imagery and finally, one study [21] uses X-band Cosmo-sky MED imagery. Particularly, in the LAC studies C-band Sentinel-1 is preferred five times [9, 12, 14, 16, 21], and in one study X-band Cosmo-sky MED imagery is preferred [21]. Multitemporal approaches are preferred in all case studies, with only one case [9] also using single images. Three researchers prefer to use interpretation for landslide detection and mapping, in particular, two in LAC [9,21] using change detection analysis in C-band Sentinel-1 the former, and X-band Cosmo-sky MED and C-band Sentinel-1 the latter.

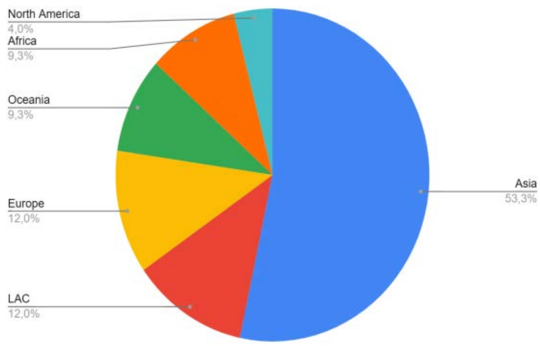

Fig. 1 Distribution of study areas across continents, represented as percentages. The chart highlights a greater concentration of test cases in Asia compared to other regions.

Regarding the techniques used, four studies apply different CNNs for landslide detection or semantic segmentation [11, 12, 13, 14], two of them in LAC [12, 14], the remaining authors apply thresholds [8], spatial correlation [24], statistical analysis [15], OBIA [17], segmentation [22, 23], empirical models in a global study including LAC countries [16], and supervised learning CART [19].
Surprisingly, among the 17 first authors, there is no one from LAC and only two among 69 (about 3%) as co-authors [10, 21]. It is also surprising that the Argentinian SAR L-band SAOCOM, which operates in 4 polarisations and is very well suited for landslide detection [1] using amplitude, has not been taken into account since its availability.

5. DISCUSSION

This study, along with the findings of [1], confirms that SAR amplitude can be effectively used to detect new landslides in LAC (e.g. Fig. 2 and 3). Seventy-five case studies demonstrate that a range of techniques, including qualitative interpretation and quantitative analysis, can be applied successfully across various countries, geo settings, and types of landslides.

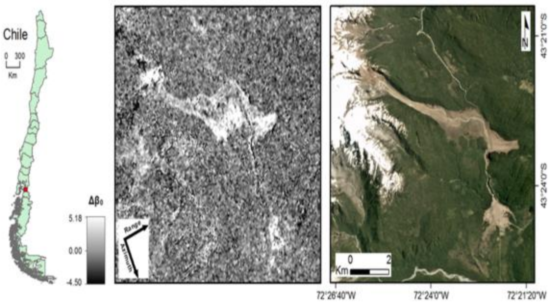

Fig. 2 The Villa Santa Lucia landslide in (Chile) [26]. On the left: is the landslide location, in the middle: the measure of SAR amplitude changes, on the right: is the landslide in the optical image (https://www.planet.com).

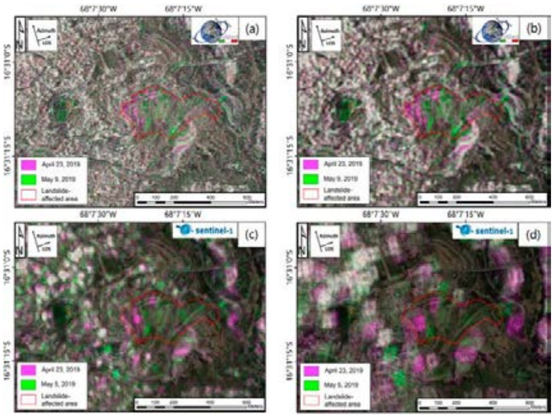

Fig. 3 The results of the landslide-affected area mapping using amplitude change detection approaches in Bolivia: (**a**) color composition of the pre and post-failure COSMO-SkyMed sigma0 bands; (**b**) color composition of the COSMO-SkyMed GLCM variance feature; (**c**, **d**) color composition of the pre and post-failure Sentinel 1 sigma0 bands of the ascending and descending geometry, respectively [21].

SAR amplitude-based analysis, which operates day and night and acquires imagery regardless of weather, offers unique opportunities for continuous detection—especially in regions with persistent cloud cover, making it particularly valuable for LAC. (e.g. Fig. 3).

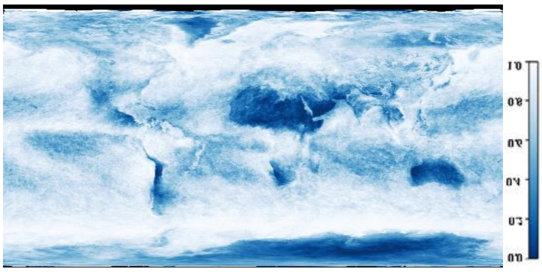

Fig. 3 The cloud fraction measured from MODIS (NASA) for December 2023 (https://neo.gsfc.nasa.gov/view.php?datasetId=MODAL2_M_CLD_FR&year=2023).

The C-band Sentinel-1 free and open-access facility has long been the most used by the authors. This is not surprising given the additional features of global coverage, high revisit frequency and good spatial resolution [1] provided by the constellation operated by the Copernicus joint initiative of the European Commission (EC) and the European Space Agency (ESA).

According to [25], in LAC there are several space agencies. Argentina has the “Comisión Nacional de Actividades Espaciales” (CONAE) founded in 1991; In Brazil exists the “Comissão Nacional de Atividades Espaciais” (CNAE), founded in 1963; the “Instituto Nacional de Pesquisas Espaciales” (INPE), founded in 1971, and the “Agência Espacial Brasileira” (AEB), founded in 1994. Perú has the “Agencia Espacial del Perú” (AEP), founded in 1974; In Uruguay exists the “Centro de Investigación y Difusión Aeronáutico-Espacial” (CIDA-E), founded in 1975; In Colombia, the “Comisión Colombiana del Espacio” (CCE), founded in 2006; Venezuela counts with the “Agencia Bolivariana para Actividades Espaciales” (ABAE), founded in 2008; Costa Rica has the “Asociación Centroamericana de Aeronáutica y el Espacio” (ACAE), founded in 2010; In México exists the “Agencia Espacial Mexicana” (AEM), founded in 2010; Bolivia has the “Agencia

Boliviana Espacial" (ABE), founded in 2012; and in Paraguay, the "Agencia Espacial de Paraguay" (AEP), founded in 2014. Despite the existence of these space research institutions, which have a tradition of several decades, we did not find any studies using SAR amplitude applied to landslides arising from these institutions. It is also surprising that the Argentinian SAR L-band SAOCOM, which operates in 4 polarisations and is very well suited for landslide detection [1] using amplitude, has not been taken into account since its availability. In Latin America and the Caribbean, there is a strong need for expanded training and knowledge in the use of SAR amplitude for landslide mapping, along with the establishment of institutional links and collaborative projects with international researchers. These steps are essential for building local capacity and advancing hazard-mapping capabilities in the region. Organizations such as the International Geographical Union (IGU)-Hazard and Risk Commission (https://igu-online.org/organization/commissions/), which actively promotes science outreach in hazard contexts, are instrumental in facilitating these goals.

By fostering international collaboration and knowledge exchange, they can help empower Latin American researchers to make impactful contributions to landslide risk assessment and mitigation efforts.

6. CONCLUSIONS

In this work, we examined the state of art of landslide detection and mapping using SAR extending the analysis carried out by a previous research. We added papers published between 2020 and 2024, with a greater emphasis on studies carried out in LAC and by LAC researchers, in particular on the use of SAR amplitude for landslide detection.

Among the first authors of the studies analyzed, no one from LAC and only two as co-authors, from Colombia and Bolivia.

Analysis of the distribution of study areas reveals that 75 new study areas in all continents are considered, with Asia being the most studied (53.3%) and LAC (12%). Despite the existence of twelve spatial agencies in LAC, we did not find any studies using SAR amplitude applied to landslides arising from these institutions. The amplitude of the Argentine satellite SAOCOM, operated by CONAE, could be useful for detecting landslides, but it has not been used yet.

Probably in LAC, local capacity in the use of SAR amplitude for landslide mapping is missing. In this regard, international organizations, such as the International Geographical Union (IGU)-Hazard and Risk Commission can contribute to the exchange of knowledge and thus, help empower Latin American researchers to make impactful contributions to landslide risk assessment and mitigation labors.

7. REFERENCES

[1] A.C. Mondini, F. Guzzetti, K-T Chang, O. Monserrat, T.R. Martha and A. Manconi, Landslide failures detection and mapping using Synthetic Aperture Radar: Past, present and future. Earth-Science Reviews, 216, pg. 2-33 (2021).

[2] S. Fidan, H. Tanyaş, A. Akbaş, L. Lombardo, D. Petley and T. Gorum. Understanding fatal landslides at global scales: a summary of topographic, climatic, and anthropogenic perspectives. Nat Hazards 120, pg. 6437–6455 (2024).

[3] M.J. Froude and D.N. Petley, Global fatal landslide occurrence from 2004 to 2016, Nat. Hazards Earth Syst. Sci., 18, pg. 2161–2181 (2018).

[4] F. Guzzetti, A.C. Mondini, M. Cardinali, F. Fiorucci, M. Santangelo, and K-T Chang, Landslide inventory maps: New tools for an old problem, Earth-Science Reviews, 112, 1–2, pg. 42-66 (2012).

[5] D. Gomez, E.F. García and E. Aristizábal, Spatial and temporal landslide distributions using global and open landslide databases. Nat Hazards 117, 25–55 (2023).

[6] S.A. Sepúlveda and D.N. Petley. Regional trends and controlling factors of fatal landslides in Latin America and the Caribbean, Nat. Hazards Earth Syst. Sci., 15, pg. 1821–1833 (2015).

[7] C.P. Cardozo, G. Toyos and V. Baumann. Landslide susceptibility zonation in the Tartagal River basin, Sierras Subandinas, Salta, Argentina. Andean Geology, 48, 1, pg. 75-93 (2021).

[8] K. Burrows, O. Marc and D. Remy, Using Sentinel-1 radar amplitude time series to constrain the timings of individual landslides: a step towards understanding the controls on monsoon-triggered landsliding, Nat. Hazards Earth Syst. Sci., 22, pg. 2637–2653 (2022).

[9] M. Santangelo, M. Cardinali, F. Bucci, F. Fiorucci and A.C. Mondini, Exploring event landslide mapping using Sentinel-1 SAR backscatter product. Geomorphology, 397, 15, pg. 1-29 (2022).

[10] V. Böhm, W.J. Leong, R. Bal Mahesh, I. Prapas, E. Nemni, F. Kalaitzis, S. Ganju and R. Ramos-Pollan. SAR-based landslide classification pretraining leads to better segmentation, arXiv, 2022, 36° Annual Conference on Neural Information Processing Systems - NeurIPS, pg. 7 (2022).

[11] L. Chen, Z. Li, C. Song, J. Xing, X. Cai, Z. Fang, R. Luo and Zi. Automatic detection of earthquake triggered landslides using Sentinel-1 SAR imagery based on deep learning. International Journal of Digital Earth, 17(1), pg. 1-22 (2024).

[12] L. Nava, A.C. Mondini, K. Bhuyan, C. Fang, O. Monserrat, A. Novellino and F. Catani, Sentinel-1 SAR-based Globally distributed landslide detection by Deep Neural Networks, earthXiv. Preprint version (2024).

[13] L. Nava, K. Bhuyan, S.R. Meena, O. Monserrat and F. Catani. Rapid Mapping of Landslides on SAR Data by Attention U-Net. Remote Sensing, 14, 6, pg. 1449 (2022).

[14] W. Wang, M. Motagh, Z. Xia, S. Plank, Z. Li, A. Orynbaikyzy, C. Zhou and S. Roessner, A framework for automated landslide dating utilizing SAR-Derived Parameters Time-Series, An Enhanced Transformer Model, and Dynamic Thresholding. International. Journal of Applied Earth Observation and Geoinformation, 129 (2024).

[15] J. Jung and S.-H. Yun, Evaluation of Coherent and Incoherent Landslide Detection Methods Based on Synthetic Aperture Radar for Rapid Response: A Case Study for the 2018 Hokkaido Landslides. Remote Sensing, 12-2, 265 (2020).

[16] E. Lindsay, J. Ganerød, A. Devoli, G. Reiche, J. Nordal, S. Frauenfelder, R. Tokle, L.-C. Understanding Landslide Expression in SAR Backscatter Data: A Global Study. Preprints (2023).

[17] S.-Y Lin, C.-W. Lin and S. van Gasselt. Processing Framework for Landslide Detection Based on Synthetic Aperture Radar (SAR) Intensity-Image Analysis. Remote Sens., 4, pg. 644 (2021).

[18] P.J. Mayuga, S.F. Tiongson, J.J. Abao, J.M. Mendoza, G.A. Pernez and R.Ramirez, Landslide Area Mapping Using Synthetic Aperture Radar (SAR) Data: the Case of The 2018 Naga Landslide. IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium, Kuala Lumpur, Malaysia, pg. 7883-7886 (2022).

[19] S. Phakdimek, D. Komori and T. Chaithong, Combination of optical images and SAR images for detecting landslide scars, using a classification and regression tree. International Journal of Remote Sensing, 44, 11, pg. 3572–3606 (2023).

[20] M. Ao, L. Zhang, Y. Dong, L. Su, X. Shi, T. Balz and M. Liao. Characterizing the evolution life cycle of the Sunkoshi landslide in Nepal with multi-source SAR data. Sci Rep 10, 17988 (2020).

[21] M. Shan, F. Raspini, M. Del Soldato, A. Cruz and N. Casagli, Mapping and Pre- and Post-Failure Analyses of the April 2019 Kantutani Landslide in La Paz, Bolivia, Using Synthetic Aperture Radar Data. Remote Sens., 15, 22, 5311(2023).

[22] P. Miele, M. Di Napoli, A. Novellino, D. Calcaterra, J. J. Mallorqui and D. Di Martire, SAR data and field surveys combination to update rainfall-induced shallow landslide inventory, Remote Sensing Applications: Society and Environment, 26, 100755(2022).

[23] A. Manconi, A.C. Mondini, and the Alp Array working group: Landslides caught on seismic networks and satellite radars, Nat. Hazards Earth Syst. Sci., 22, pg. 1655–1664 (2022).

[24] A.A.J. Deijns, O. Dewitte, W. Thiery, N. d'Oreye, J.-P. Malet, and F. Kervyn, Timing landslide and flash flood events from SAR satellite: a regionally applicable methodology illustrated in African cloud-covered tropical environments, Nat. Hazards Earth Syst. Sci., 22, pg. 3679–3700 (2022).

[25] J. Gocłowska-Bolek and D. Blinder. La investigación espacial latinoamericana. Saber y tiempo, 1, 2, pg. 16-32 (2018).

[26] A.C. Mondini, M. Santangelo, M Rocchetti, E. Rossetto, A. Manconi, O. Monserrat, Sentinel-1 SAR Amplitude Imagery for Rapid Landslide Detection. Remote Sens. 11, 760. (2019).