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The Future of National GNSS-Geomonitoring Infrastructures in Switzerland

White Paper

John Clinton

Alain Geiger

Simon Häberling

Florian Haslinger

Markus Rothacher

Adrian Wiget

Urs Wild

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Adresse der Schweizerischen Geodätischen Kommission:

Institut für Geodäsie und Photogrammetrie
Eidg. Technische Hochschule Zürich
ETH Zürich
8093 Zürich
Switzerland

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F. Haslinger, A. Geiger, J. Müller-Gantenbein, A. Wiget
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VORWORT

Die Anwendungsgebiete der globalen Navigationssatelliten-Systeme (GNSS), allen voran des Global Positioning System GPS, wurden seit deren ersten Verfügbarkeit stark erweitert. Anfänglich für militärische Zwecke entwickelt und aufgebaut, wurden sie rasch auch zivil genutzt. Heute reichen die Anwendungen von Positionierung, Navigation und Tracking über Zeitbestimmung und -synchronisierung bis hin zu atmosphärischen Beobachtungen für die Meteorologie oder die Funktechnologie. Immer neue Anwendungen, welche zuweilen exotisch anmuten, kommen hinzu. Die Einsatzgebiete sind zu Lande, zur See, in der Luft und im Weltraum. In verschiedensten Lebensbereichen nutzen wir die Signale der Navigationssatelliten, im Beruf wie in der Freizeit, im Geschäftsleben, in der Wissenschaft, in der Industrie oder im Sport. GNSS wird als Primärsensor wie auch als Ergänzungskomponente verwendet.

Bereits Mitte der 1980er Jahre haben das Bundesamt für Landestopografie (swisstopo), das Astronomische Institut der Universität Bern (AIUB) und das Institut für Geodäsie und Photogrammetrie (IGP) der ETH Zürich im Rahmen der Schweizerischen Geodätischen Kommission (SGK) für geodätische Präzisionsanwendungen das GNSS-Testnetz Turtmann aufgebaut und vermessen (vgl. Bände 45 und 51 dieser Publikationsreihe). Es diente als Basis für verschiedenste praxisnahe Empfängertests und Untersuchungen, z.B. dem Studium troposphärischer Modelle in der Berner GPS Software des AIUB. Im Anschluss daran hat swisstopo hochpräzise GNSS-Netze wie das Netz NEOTEKTONIK für regionale Deformationsmessungen in der Nordschweiz oder das GNSS-Landesnetz für die Landesvermessung LV95 aufgebaut, sowie diverse lokale Referenznetze für Tunnelbauten und Staumauerüberwachungsnetze.

Seit den 1990er Jahren werden weltweit auch zivile permanente GNSS-Empfangsstationen betrieben, u.a. zur Festlegung der geodätischen Bezugsrahmen und für die hochpräzise Erdüberwachung, das sog. «Geomonitoring». In der Schweiz hat swisstopo das Automatische GNSS Netz der Schweiz AGNES aufgebaut, welches als «Mehrzweck-Netz» für die Landesvermessung und den Betrieb von Positionierungsdiensten sowie als Referenznetz zur landesweiten Bestimmung der geometrischen Veränderungen der Erdoberfläche und für weitere der angesprochenen vielseitigen Anwendungen dient. Nebst den GNSS-Empfangsstationen sind zusätzliche betriebliche Komponenten erforderlich, z.B. für die Kommunikation und Datenverarbeitung. Erdbeobachtungsnetze werden somit zu nationalen Infrastrukturanlagen. Zudem erfordern globale wie regionale Präzisionsanwendungen eine breite internationale Zusammenarbeit mit Partnerinstitutionen und weiteren Betreibern von GNSS-Permanentnetzen, beispielsweise für die zivile Bestimmung der Satellitenbahnen, wie sie das Center for Orbit Determination in Europe (CODE) am AIUB durchführt. Die in der SGK vertretenen Institutionen und Firmen engagieren sich daher in internationalen Organisationen und Diensten wie dem International GNSS Service (IGS) und der IAG Reference Frame Sub-Commission for Europe EUREF.

Bei der Erweiterung und Erneuerung von AGNES, insbesondere dessen Verdichtung und Ergänzung mit neuen Stationen und neuen Komponenten, ist die Zusammenarbeit mit weiteren Institutionen sinnvoll und erwünscht. Denn wichtig sind gute Kooperationen auch bei interdisziplinären Anwendungen und Studien. Beobachtungsnetze können von Synergien bei den genannten Infrastrukturanlagen profitieren, aber auch von der Kollokation der Sensoren unterschiedlicher Messnetze in unmittelbarer Nähe zueinander. So kam es zu wertvollen Kontakten zwischen swisstopo und dem Schweizerischen Erdbebendienst (SED), welcher seinerseits ein Messnetz mit seismischen Stationen in der Schweiz betreibt. Im Weiteren wurde der Kontakt zur Professur für Mathematische und Physikalische Geodäsie (MPG) am IGP der ETH Zürich gesucht, wo Simon Häberling an Untersuchungen über «*Theoretical and Practical Aspects of High-Rate GNSS Geodetic Observations*» arbeitete (vgl. Band 95 dieser Publikationsreihe).

Fachleute von swisstopo, der ETH Zürich und des SED haben sich deshalb zusammengesetzt, um aktuelle und künftige Fragen und Bedürfnisse optimaler nationaler GNSS Infrastrukturen und des Datenaustausches bei der Kombination von GNSS-Empfängern und Seismometern zu besprechen. Im vorliegenden Bericht – in der Form eines White Papers – sind die Ergebnisse der Diskussionen zusammengefasst und Empfehlungen zum Aufbau der zukünftigen nationalen GNSS-Erdbeobachtungsinfrastruktur der Schweiz abgeleitet. Es ist zu hoffen, dass diese Empfehlungen diskutiert, weiterbearbeitet oder mit Alternativvorschlägen erweitert werden.

Die drei Institutionen bilden nur den Kern einer Gruppe, welche auch weiteren Interessenten und Institutionen innerhalb und ausserhalb der SGK offensteht. Dabei denken wir an das Astronomische Institut der Universität Bern (AIUB), das Bundesamt für Meteorologie und Klimatologie (MeteoSchweiz), das Bundesamt für Umwelt (BAFU), das Bundesamt für Energie (BFE), die Eidgenössischen Forschungsanstalt für Wald, Schnee und Landschaft (WSL) und das Institut für Schnee- und Lawinenforschung SLF, weitere Institute der ETH Zürich und der EPF Lausanne oder den Flugsicherungsdienst skyguide. Den namentlich erwähnten Institutionen wurde das vorliegende Dokument denn auch zur Stellungnahme vorgelegt.

Der vorliegende Bericht reiht sich einerseits ein in die Publikationen von Arbeiten betreffend Untersuchungen und Entwicklungen zu GPS und GNSS der Schweizerischen Geodätischen Kommission (SGK). Andererseits steht er in engem Zusammenhang mit der Dokumentation des Aufbaus der neuen Landesvermessung LV95 von swisstopo. Da wissenschaftliche Aspekte und Fragen der interdisziplinären Anwendungen dominieren, hat die SGK der Publikation in der Reihe «Geodätisch-geophysikalische Arbeiten in der Schweiz» zugestimmt. Wir danken den Autoren für ihren wertvollen Beitrag zur Diskussion der Bedürfnisse und der Formulierung entsprechender Empfehlungen für optimale nationale GNSS Geomonitoring-Infrastrukturen in der Schweiz. Den drei beteiligten Institutionen danken wir, dass sie dieses Engagement ermöglicht haben. Und schliesslich danken wir der SCNAT für die Übernahme der Druckkosten.

Prof. Dr. A. Geiger	**Dr. F. Haslinger**	**A. Wiget, Dipl. Ing. ETH**
Präsident der Schweizerischen Geodätischen Kommission	stv. Direktor Schweiz. Erdbebendienst	Quästor der Schweizerischen Geodätischen Kommission
Professor am MPG/IGP ETH Zürich	Leiter «Unterstützung und Spezialprojekte»	Leiter Geodäsie von swisstopo (2006-2016)

PREFACE

Depuis leur création, le champ des applications des systèmes de navigation par satellite (GNSS) et en particulier du système de positionnement global (GPS), se sont rapidement étendus. Initialement développés et construits pour des objectifs militaires, les GNSS ont rapidement été utilisés à des fins civiles. De nos jours, les applications vont du positionnement à la navigation, du transfert de temps à la synchronisation d'horloges, et même jusqu'au monitorage de l'atmosphère bien utile en météorologie et en techniques de télécommunication. De nouvelles applications même parfois exotiques continues à voir le jour. Elles trouvent leur terrain de jeu sur Terre, sur la mer, dans les airs et dans l'espace. Les signaux des satellites de navigation font également partie de nos vies quotidiennes, autant lors de nos activités professionnelles, que de lors notre temps libre, elles accompagnent nos activités économiques et scientifiques, comme dans l'industrie et le sport. Dans le futur, les GNSS seront souvent utilisés comme senseur principal ou comme composants complémentaires d'autres systèmes.

Au milieu des années 1980, sous l'égide de la Commission Géodésique Suisse (CGS), l'Office Fédéral de Topographie swisstopo, l'Institut Astronomique de l'Université de Berne (AIUB) et de l'Institut de Géodésie et de Photogrammétrie (IGP) de l'EPF de Zurich ont réalisés et mesurés un réseau test GNSS de haute précision à Tourtemagne (voir les volumes 45 et 51 de cette série de publications). Ce réseau a servi de référence pour de nombreux tests pratiques de récepteurs et a permis d'amélioré la modélisation de la troposphère dans le logiciel Bernese GNSS software, développé à l'Université de Berne. Par la suite, swisstopo a établi et déterminé des réseaux GNSS de haute-précision, comme le réseau de déformation régional NEOTEKTONIK dans le nord de la Suisse, ou comme le réseau « MN95 » avec plus de 200 points matérialisés. De plus, swisstopo s'appuie depuis de nombreuses années les GNSS pour une grande variété de réseaux de référence locaux pour la construction de tunnels et la surveillance de barrages. Depuis les années 1990 et dans le monde entier, la détermination et la maintenance des cadres de référence géodésiques ainsi que le géomonitorage de haute précision ont commencés à être réalisés de façon routinière et continue grâce aux stations GNSS permanentes. En Suisse, swisstopo a mis en place le réseau AGNES, the Automatic GNSS Network of Switzerland. C'est un réseau à usages multiples utilisé pour la mensuration national, pour le service de positionnement officiel swipos et de nombreuses autres applications. De plus, il sert de cadre de référence pour la surveillance nationale des changements géométriques ainsi que des mouvements de la croute terrestre. En plus des récepteurs GNSS, d'autres composantes sont nécessaires, comme les lignes de communication et les outils d'analyse des données. Par conséquent, les réseaux de géomonitorage sont une partie importante de l'infrastructure nationale de base. De surcroit, les applications globales et régionales nécessitent des coopérations internationales avec des institutions et des opérateurs d'autres réseaux GNSS permanents. Par exemple, la détermination civile d'orbites précises des satellites par le Center for Orbit Determination in Europe (CODE) à l'AIUB. A cet effet, les institutions ainsi que les firmes représentées dans le cadre de la CGS sont engagées dans de nombreuses organisations et services internationaux comme l'International GNSS Service (IGS) ou bien encore l'IAG Reference Frame Sub-Commission for Europe (EUREF).

Dans la perspective de l'expansion, du renouvellement et surtout de la densification du réseau AGNES munis de nouveaux composants, les collaborations avec d'autres institutions sont judicieuses et souhaitables. Il est également important que de bonnes coopérations interdisciplinaires tant au niveau des applications qu'au niveau des études prennent forment de façon concrète. Les réseaux de monitorage peuvent ainsi bénéficier de la synergie des infrastructures mais également de la colocation des senseurs et enfin de la proximité des réseaux proches des stations GNSS. En conséquence, des contacts fructueux entre swisstopo et le Service Sismologique Suisse (SED) qui exploite un réseau de stations sismologiques en Suisse sont souhaitables. De plus, des contacts ont été élaborés avec la chaire de Géodésie Mathématique et Physique (MPG) à l'IGP de l'EPF de Zurich, dans laquelle Simon Häberling travaillait sur une thèse de doctorat «*Theoretical and Practical Aspects of High-Rate GNSS Geodetic Observations*» (voir vol. 95 de cette série de publications).

Des experts de chez swisstopo, de l'EPF de Zurich et du SED se sont donc rencontrés afin de discuter des questions actuelles et des besoins futurs concernant l'infrastructure national des réseaux GNSS, ainsi que de l'échange de données dans l'optique d'une combinaison des données GNSS et sismiques. Les résultats des discussions et les conclusions portant sur l'établissement de l'infrastructure du futur réseau national de géomonitorage GNSS en Suisse sont publiés dans ce White Paper. Nous espérons que nos recommandations seront discutées, éventuellement implémentées, sinon pour le moins complétées par des propositions alternatives. Ces trois institutions forment seulement le coeur d'un groupe qui peut être élargi, selon leurs éventuels intérêts, à d'autres partenaires qui ne sont pas nécessairement membres de la Commission Géodésique Suisse. A ce propos, nous voulons saluer les contributions de l'Institut d'Astronomie de l'Université de Berne (AIUB), de l'Office Fédérale de Météorologie et de Climatologie (MeteoSwiss), de l'Office Fédérale de l'Environnement (OFEV), de l'Office Fédérale de l'Énergie (OFEN), de l'Institut Fédéral de Recherches sur la Forêt, la Neige et le Paysage (WSL), de l'Institut pour l'Étude de la Neige et des Avalanches (SLF), ainsi que d'autres Instituts des EPF de Zurich et de Lausanne et du Service de la Navigation Aérienne skyguide. Pour cette raison, une ébauche de ce document a été envoyée pour consultation aux institutions précitées, afin qu'elles puissent nous faire parvenir leurs commentaires.

Ce rapport fait partie des publications dans le cadre des travaux de la Commission Géodésique Suisse qui concernent les recherches et les développements qui s'apparentent au GPS et aux GNSS. Ce document est également une contribution à la réalisation du nouveau cadre de référence géodésique « MN95 » de swisstopo. Dans la mesure où les aspects scientifiques interdisciplinaires y sont traités de façon dominante, la CGS s'est accordée à publier ce White Paper dans la série de publications «Geodätisch-geophysikalischen Arbeiten in der Schweiz». Nous remercions les auteurs pour leurs contributions de hautes valeurs et pour les discussions fructueuses qui ont permis de définir et de formuler des recommandations appropriées pour l'avenir de l'infrastructure de géomonitorage par GNSS en Suisse. Nous remercions également les trois institutions qui ont initiés ces travaux. Finalement, nous remercions l'Académie Suisse des Sciences (SCNAT) pour la prise en charge des frais d'impression.

Prof. Dr. A. Geiger
Président de la Commisson
Géodesique Suisse
Professor de la MPG/IGP
ETH Zurich

Dr. F. Haslinger
Directeur Adjoint
Service Sismologique Suisse
Chef de «Support and
Special Projects»

A. Wiget, Dipl. Ing. ETH
Quaestor de la Commission
Géodesique Suisse
Chef de la Géodesie swisstopo
(2006-2016)

FOREWORD

The field of applications of the Gobal Navigation Satellite Systems (GNSS), and in particular the Global Positioning System GPS, has been rapidly expanding since its inception. Initially developed and constructed for military use, GNSS were rapidly and broadly adopted for civil purposes. Today, applications range from positioning, navigation and tracking to timing and time synchronisation or monitoring of the atmosphere for meteorology and radio engineering. New applications and uses continue to be developed, some of which appear quite exotic. The areas of operation span land, sea, air and space. In almost all facets of modern life we use the signals from the navigation satellites, on the job and in our spare time, for business, science, industry and sports. GNSS can be used as principal sensor and also as a complimentary but crucial component for other systems.

In the mid 1980s, the Swiss Geodetic Commission (SGC), comprised of the Federal Office of Topography swisstopo, the Astronomical Institute of the University of Bern (AIUB) and the Institute of Geodesy and Photogrammetry (IGP) of the ETH Zurich, established and surveyed the GNSS test network ‘Turtmann’ targeting geodetic testing and high precision applications (see volumes 45 und 51of this publication series). The network served as a reference for various practical receiver tests and studies, e.g. to improve the tropospheric modelling in the Bernese GNSS Software developed by the AIUB. Subsequently, swisstopo has established and observed high-precision GNSS networks like the network NEOTEKTONIK in northern Switzerland for regional deformation measurements or the GNSS network with 200 sites for the national reference frame «LV95». In addition, swisstopo used and still uses GNSS for a variety of local reference networks for tunnel constructions and for dam control.

Since the 1990s, it has become routine for civil permanent GNSS stations to be operated all over the world for the determination and maintenance of geodetic reference frames and for high precision monitoring of the earth, or ‘geomonitoring’. In Switzerland, swisstopo has established AGNES, the Automatic GNSS Network of Switzerland. It is a ‘multi-purpose network’ for national geodetic surveys and for the operation of official positioning services (swipos) as well as for providing the reference frame for the nationwide determination of geometrical changes and movements of the earth crust and for various other applications. In addition to the continuously operating GNSS reference stations, other components and networks are necessary, e.g. for communication and data processing. Therefore networks for geomonitoring have become a basic and important national infrastructure. Moreover, global as well as regional high precision applications require broad international cooperation with associated institutions and operators of other networks of continuously operating GNSS reference stations, i.e. for the civil determination of satellite ephemeris like the Center for Orbit Determination in Europe (CODE) at the AIUB. The institutions and companies represented in the SGC are engaged in many international organisations and services like the International GNSS Service (IGS) and the IAG Reference Frame Sub-Commission for Europe (EUREF).

As swisstopo moves towards the expansion and renewal of AGNES, especially its densification and extension with new stations, new components and sensors, the collaboration with additional institutions is reasonable and desirable. Furthermore close cooperation is important for interdisciplinary applications and studies. Monitoring networks can profit from synergies in the named infrastructures but also from the collocation of sensors of other networks in immediate proximity to the GNSS sites. Therefore valuable contacts were established between swisstopo and the Swiss Seismological Service (SED), who operate the national monitoring network of seismic stations in Switzerland. In addition, the chair of Mathematical and Physical Geodesy (MPG) in the IGP at the ETH Zurich was contacted, where Simon Häberling was working on «*Theoretical and Practical Aspects of High-Rate GNSS Geodetic Observations*» (see vol. 95 of this publication series).

Experts of swisstopo, the ETH Zurich and the SED came together to discuss actual and future questions and needs of optimal national GNSS infrastructures and of the data exchange when combining GNSS receivers and seismometers in monitoring networks. The results of these discussions and the conclusions for the establishment of the future national GNSS-geomonitoring infrastructure of Switzerland are published in this White Paper. We hope that the recommendations are discussed and eventually implemented or at least complemented with alternative proposals.

The three institutions form the core of a group which could be extended upon request to further stakeholders within and outside the Swiss Geodetic Commission. In particular we would welcome contributions from the Astronomical Institute of the University of Bern (AIUB), the Federal Office of Meteorology and Climatology (MeteoSwiss), the Federal Office for the Environment (FOEN), the Federal Office of Energy (SFOE), the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) and the Institute for Snow and Avalanche Research (SLF), other institutes of the ETH Zurich and of the EPF Lausanne or the air navigation services provider skyguide. For this reason the draft of this document has been submitted to the named institutions for comments.

This report forms part of the publications of work within the Swiss Geodetic Commission SGC dealing with research and developments related to GPS and GNSS. This document is also a contribution to the new national geodetic survey «Landesvermessung LV95» by swisstopo. Since scientific aspects and questions regarding interdisciplinary applications are highlighted, SGC has agreed to publish this «White Paper» in the series «Geodätisch-geophysikalische Arbeiten in der Schweiz». We thank the authors for their very valuable contributions to the discussions of the needs and requirements and the formulation/definition of the appropriate recommendations for optimal GNSS-Geomonitoring infrastructures in Switzerland. We thank the three institutions that have enabled this engagement. And finally we thank the Swiss Academy of Sciences (SCNAT) for covering the printing costs.

Prof. Dr. A. Geiger
President of the Swiss
Geodetic Commission
Professor at MPG/IPG
ETH Zurich

Dr. F. Haslinger
Deputy Director
Swiss Seismological Service
Head of «Support and
Special Projects»

A. Wiget, Dipl. Ing. ETH
Quaestor of the Swiss
Geodetic Commission
Head of Geodesy at swisstopo
(2006-2016)

1 Zusammenfassung

Dieses Dokument entwirft eine Vision für die Zukunft der GNSS-Geomonitoring Infrastrukturen in der Schweiz, welche von den drei Schlüssel-Institutionen, dem Bundesamt für Landestopografie swisstopo, dem Schweizerischen Erdbebendienst (SED) und dem Institut für Geodäsie und Photogrammetrie (IGP) der ETH Zürich entwickelt wurde, und die von der Schweizerischen Geodätischen Kommission und der Schweizerischen Geophysikalischen Kommission unterstützt wird. Netze von GNSS-Permanentstationen erbringen Dienstleistungen für die Gesellschaft und haben einen klaren ökonomischen und kommerziellen Wert. Dennoch behandelt dieses Dokument primär wissenschaftliche Aspekte der kontinuierlichen GNSS-Überwachung. Globale Standards und jüngste wissenschaftliche Erkenntnisse und Trends werden studiert. Dabei wird der Hauptfokus auf die Darlegung der Fortschritte im Netzwerk-Design, auf die Netzdichte, die Hardwarekomponenten und die Kombination mit anderen Sensoren, das Datenmanagement, den Datenaustausch und die Datenprodukte gelegt. Das automatische GNSS Netzwerk der Schweiz AGNES ist ein hochqualitatives, automatisiertes Multifunktions-Netzwerk, welches Anwendungen der geodätischen Landesvermessung, der Positionierung, der Geodynamik und der Meteorologie ermöglicht bzw. unterstützt. Während es bezüglich den Stationsabständen und der Qualität der Instrumentierung gleichwertig ist mit anderen fortschrittlichen GNSS-Netzen, scheinen Verbesserungen in der Organisation des Datenmanagements und der Datenverteilung machbar zu sein, besonders für Echtzeit- und kurzfristige Anwendungen sowie in der Koordination mit anderen Anspruchsgruppen. Eine spezielle Erkenntnis ist, dass weitergehende Verstärkungen der bestehenden Anwendungen und die Ausdehnung in Richtung der Seismologie und lokaler seismologischer Überwachung das Potenzial hätten, signifikant zur Abschätzung der allgemeinen seismischen Bedrohung in der Schweiz beizutragen. Werden die in diesem Dokument dargelegten Empfehlungen befolgt, so können diese zu einem besseren Verständnis der aktuellen tektonischen und seismischen Prozesse beitragen. Zudem können dadurch künftige Erdbeben-Frühwarnsysteme sowie andere Systeme zur raschen Charakterisierung von Ereignissen unterstützt werden, indem neue Erkenntnisse, Redundanzen und eine höhere Zuverlässigkeit ermöglicht werden.

Die folgenden Schlüssel-Empfehlungen werden als Massnahmen vorgeschlagen:

1. **Örtliche Verdichtung** des Basisnetzes von AGNES durch neue Stationen, welche für Studien der Geodynamik geeignet sind. Die Ziele sind
   i) generelle Verdichtung auf Stationsabstände von 10-20 km;
   ii) verbesserte Höhenverteilung in Bergregionen;
   iii) ausgewählte Verdichtungen in Regionen mit erhöhtem seismischem Risiko.

2. **Kollokation** von ausgewählten AGNES-Stationen mit seismischen Stationen und meteorologischen Sensoren. Zumindest der Erdbebendienst, swisstopo und MeteoSchweiz sollen einander bei der **Planung künftiger neuer Beobachtungsstationen** konsultieren.
3. Die **Infrastruktur** soll auf allen AGNES-Stationen sowie auf Stationen von Partner-Netzwerken verbessert werden, sodass Abtastraten von 20 Hz möglich sind. Die Kommunikation soll so verbessert und etabliert werden, dass genügende Bandbreiten bereitgestellt und minimale Latenzzeiten garantiert werden können. swisstopo soll eine Verarbeitungskette einrichten, welche die Auswertung hoher GNSS-Datenraten mit minimalen Latenzzeiten ermöglicht.
4. swisstopo und der Schweizerische Erdbebendienst etablieren einen Rahmen zur **Integration hoher GNSS-Datenraten in den Auswerteprozessen der seismischen Netze**, einschliesslich der Archivierung der Verschiebungsraten bei Ereignissen in den Zeitreihen des Erdbebendienstes mit minimalen Latenzzeiten.
5. swisstopo soll **Standards und Richtlinien** definieren, welche von allen Institutionen angewandt und befolgt werden, die entweder hoch-qualitative GNSS-Permanentstationen aufbauen oder temporäre Installationen mit niedrigeren Qualitätsansprüchen betreiben, welche mit AGNES kombiniert werden sollen. Aufkommende allgemeine Standards und Normen sollen soweit möglich und sinnvoll eingehalten werden. swisstopo soll die nationale GNSS Gemeinschaft anführen und auf internationaler Ebene koordinieren, beispielsweise mit EPOS.
6. swisstopo soll weiterhin für den **Aufbau eines nationalen Datencenters für die GNSS Auswertung und Analyse** verantwortlich sein, einschliesslich Echtzeit-Produkten und die permanente Archivierung der hochqualitativen GNSS-Daten des erweiterten automatischen GNSS-Netzwerkes.
7. **Austausch-Formate und Werkzeuge zur Verbreitung von Daten** zwischen swisstopo und den Endverbrauchern sollen definiert werden. Für wissenschaftliche Anwendungen soll eine „open data"-Politik verfolgt werden.
8. Eine **schnelle Einsatzgruppe** mit kurzen Reaktionszeiten nach einem seismischen Ereignis soll aufgebaut werden – die Ressourcen und Ausrüstungen sollen zugeteilt werden, mit klar zugewiesenen Verantwortlichkeiten.
9. Die **periodischen Messkampagnen** im GNSS-Landesnetz LV95 von swisstopo sollen weitergeführt werden, mit einer maximalen Wiederholungsperiode von sechs Jahren.

1 Résumé

Ce document décrit les grandes lignes de la vision à long terme de l'infrastructure GNSS de géo-monitorage en Suisse. Il est élaboré par trois institutions clés, l'office fédéral de topographie swisstopo, le service sismologique suisse (SED) ainsi que l'institut de géodésie et photogrammétrie de l'EPF Zurich (IGP). En outre, il est parrainé par la commission géodésique suisse ainsi que par la commission géophysique suisse. Bien que les réseaux GNSS permanents fournissent des services très utiles à la société et bénéficient d'une valeur économique évidente, ce papier traite en priorité des aspects scientifiques qui leurs sont liés. En particulier, les avancées concernant la conception des réseaux y sont décrites, de leur densité et de la pertinence de la colocation de multiples senseurs. Ceci, en analysant toute la chaîne, depuis la gestion et l'échange des données jusqu'aux produits finaux. Actuellement, le réseau GNSS permanant AGNES est de haute-qualité, polyvalent et automatique. Il trouve ses applications dans les services de positionnement, dans la mensuration nationale, en géodynamique et en météorologie. Bien que le réseau actuel puisse être considéré comme étant conforme aux réseaux les plus avancés du point de vue de la densité des stations et de l'instrumentation en place, il existe un certain potentiel d'amélioration en ce qui concerne la gestion, l'organisation et la distribution des données et des services, surtout pour ce qui est des applications en temps réel et à court terme, ainsi que du point de vue de la coordination avec les différentes parties prenantes. Une des principales conclusions de ce papier est que l'aménagement et l'augmentation des applications existantes ainsi que leur expansion au champ de la sismologie devrait pouvoir contribuer significativement à l'amélioration de l'évaluation globale des risques sismiques en Suisse. De plus, si les recommandations développées dans ce document sont mises en œuvre, elles contribueront à une meilleure connaissance des processus tectonique et sismique en cours et pourraient être bénéfiques aux applications comme les alertes précoces et la caractérisation rapide des séismes tout en augmentant la redondance et leur niveau de fiabilité général.

Voici les recommandations clés qui sont proposées :

1. **Densification spatiale** de l'épine dorsale du réseau AGNES par de nouvelles stations aux standards de qualités exigées pour des applications de géodynamique.

   Les objectifs sont :
   i) densification générale des stations avec un espacement de 10-20 km;
   ii) amélioration de la répartition en altitude des stations en région de montagne;
   iii) densification sélective des régions à forte séismicité.

2. **Colocation** de stations clés AGNES avec des stations sismiques et météorologiques. Comme mesure minimale, le SED, swisstopo et MétéoSuisse devraient se consulter lorsque **de nouvelles stations de monitorages sont planifiées**.

3. **Améliorer l’infrastructure** de toutes les stations AGNES et de leurs réseaux affiliés afin de permettre un taux d’échantillonnage de 20 mesures par seconde. Les communications doivent être mises à jour afin de disposer d’une bande passante suffisante ainsi que de temps de latence minimaux.
4. swisstopo et le SED devraient établir **un cadre clair pour l’intégration des données GNSS à hautes fréquence dans les procédures du réseau sismologique**, en intégrant les séries temporelles de déplacements des évènements sismiques dans les archives des formes d’ondes du SED, ceci avec un minimum de temps de latence.
5. swisstopo devrait définir des **standards et des lignes directrices** qui seraient appliquées par toutes les agences qui développeraient leur propre réseau permanant GNSS de haute qualité ou qui intégreraient des solutions temporaires de moindre qualité avec AGNES. Les communautés émergentes devraient suivre ces standards lorsque cela est possible. Swisstopo devrait conduire et coordonner la communauté GNSS aux échelles nationales et internationales, comme par exemple avec EPOS.
6. swisstopo devrait continuer à assurer la responsabilité de **l’établissement du centre national de données** pour le traitement et l’analyse centralisée des données GNSS, en incluant les produits temps-réel et l’archivage permanant des données GNSS de haute qualité du réseau GNSS automatique étendu.
7. **Les formats d’échange de données ainsi que les outils de diffusion** entre swisstopo et la communauté des utilisateurs finaux doivent être définis. De plus, la politique d’utilisation libre des données à des fins scientifiques doit être poursuivie.
8. **Une force d’intervention opérationnelle** devrait être établie afin de pouvoir fournir des réponses rapides après un évènement sismique significatif. Des équipements et des ressources devraient être alloués en définissant clairement la répartition des responsabilités.
9. **Les campagnes de mesures périodiques** du réseau MN95 de swisstopo devraient être continuées et répétées suivant un intervalle de temps maximal de six ans entre deux mesures.

1 Executive Summary

This document outlines a vision for the future of national GNSS-geomonitoring infrastructures in Switzerland, developed by three key institutions, the Swiss Federal Office of Topography swisstopo, the Swiss Seismological Services (SED) and the Institute of Geodesy and Photogrammetry (IGP) at ETH Zurich, and endorsed by the Swiss Geodetic Commission and the Swiss Geophysical Commission. While permanent GNSS networks provide key services for society and have a clear economic and commercial value, this paper primarily addresses scientific aspects of GNSS monitoring. Reflecting on global standards and recent scientific insights and trends, a main focus is set on outlining advances in network design, network density, encompassing hardware and multi-sensor co-location, data management and exchange, and data products. The current GNSS network for Switzerland, AGNES, is a high-quality, multi-purpose, automated network that today covers applications such as national geodetic survey, positioning services, geodynamics, and meteorology. While it is on par with many advanced networks regarding overall station spacing and instrumentation quality, improvements in data management organization and distribution seem feasible, especially with regards to real-time and short-term applications, and when coordinating with other stakeholders. One particular finding is that further enhancements of the existing applications and expansion to the field of seismology and local seismic monitoring would have the potential to contribute significantly to the overall seismic hazard assessment in Switzerland. Following the recommendations developed here will also contribute to a better understanding of the ongoing tectonic and seismic processes, and may support applications in future earthquake early warning and rapid event characterization systems, providing new insight, redundancy and higher reliability.

The following key recommendations are proposed as actions:

1. **Spatial densification** of the backbone AGNES network with new stations of geo-dynamic quality. The targets are
   i) general densification to a spacing of 10-20 km;
   ii) improved height resolution in key mountainous areas;
   iii) selective densifications in regions with elevated seismic risk.
2. **Co-locate** key stations in AGNES with seismic stations and meteorological sensors. At minimum, SED, swisstopo, and MeteoSwiss shall consult each other when **planning future new monitoring stations.**
3. **Improve infrastructure** at all AGNES and affiliated network stations to enable a sampling rate of 20 sps. Communications shall be upgraded and hardened to provide sufficient bandwidth and operated with minimum latency. swisstopo shall establish a processing chain with focus on real-time high-rate GNSS data with minimal data latency.

4. swisstopo and SED shall establish a **clear framework for integrating high-rate GNSS in seismic network procedures**, including integration of event displacements in the SED waveform archives with minimum data latency.
5. swisstopo shall define **standards and guidelines** to be applied by all agencies that may develop either high-quality permanent GNSS stations or lower quality temporary deployments that need to integrate with AGNES. Emerging community standards shall be followed where possible. swisstopo shall lead the GNSS community coordination at the national and international level, e.g. with EPOS.
6. swisstopo shall continue to be responsible for the **establishment of a national data center** for central GNSS processing and analysis, including real-time products, and the permanent archival of high-quality GNSS data of the new expanded automated GNSS network.
7. **Exchange formats and dissemination tools** between swisstopo and the end user communities shall be defined and an open data policy for scientific purposes shall be pursued.
8. An operational **task force** shall be established for rapid response after a significant seismic event – equipment and resources shall be allocated, with clear responsibilities assigned.
9. The periodic **measurement campaigns** for the swisstopo LV95 network shall be continued with a maximum re-measuring period of six years.

Table of Contents

1 Zusammenfassung..10
1 Résumé..12
1 Executive Summary..14
2 Purpose of the Document..17
3 Introduction..18
4 Present Situation of Networks, Instrumentation and Processing..20
4.1 Swiss Permanent GNSS Networks and Services..20
4.1.1 AGNES and swipos..20
4.1.2 NaGNet..23
4.1.3 Local GNSS Networks..24
4.1.4 RefNet..24
4.2 International Permanent GNSS Networks and Services..25
4.2.1 Permanent GNSS Networks and Services of Neighboring Countries..25
4.2.2 EUREF/EPN and IGS..28
4.2.3 European Plate Observing System - EPOS..29
4.2.4 Italian Co-located GNSS network RING..29
4.2.5 UNAVCO and U.S. Plate Boundary Observatory..30
4.3 Summary and Conclusions..32
5 GNSS-based Geomonitoring in Switzerland..34
5.1 Geodynamics: Swiss 4D/COGEAR..34
5.2 Meteorology..35
5.3 Monitoring of dams, glaciers, block glaciers, landslides..36
5.4 Summary and Conclusions..37
6 A step forward: Enhancement of Existing Applications and Future Developments..38
6.1 Earthquake Source Characterization and Early Warning..38
6.2 Earthquake Task Force / Aftershock Campaigns..42
6.3 Geodynamics..44
6.4 Local Monitoring..45
6.5 Meteorology..46
6.6 National Survey and Positioning Services..47
6.7 Summary..47
7 Recommendations for the National GNSS-Geomonitoring Infrastructure in Switzerland..49
References..52
Appendix A – Abbreviations..56
Appendix B – Tables..58

2 Purpose of the Document

The main goal of this document is to outline a visionary plan for national GNSS-geomonitoring infrastructures in Switzerland for the next decade. It was developed by three institutions with significant interest in this field: 1) the Swiss Federal Office of Topography swisstopo that maintains the permanent national GNSS network and provides derived products, 2) the Swiss Seismological Service (SED) at ETH Zürich that is responsible for national seismic monitoring and hazard assessment and 3) the Institute of Geodesy and Photogrammetry (IGP) at ETH Zürich as one of the key Swiss research institutions in geodesy. Other public stakeholders operating significant geomonitoring networks on national level are MeteoSwiss, the Federal Office for the Environment (FOEN/BAFU) and the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), including the Institute for Snow and Avalanche Research (SLF).

We review the purpose, actual status and current applications of permanent GNSS networks in Switzerland and compare and contrast them with other key regional and international players in order to identify current trends and define best practices for a national GNSS-geomonitoring infrastructure in Switzerland. We propose establishing a long term strategy towards tighter integration of geomonitoring networks with respect to sensor co-location, data exchange, processing strategies, products and services, in order to avoid unnecessary duplications and incompatibility of various monitoring networks. We conclude with summary statements and general recommendations concerning the proposed tasks, goals and challenges.

New ideas and remaining open questions also are incentives for further scientific collaboration and development of new synergies. While this document focuses on applications that are mainly related to the competence and responsibility of the authors' affiliations, it acts as an open invitation to other interested parties to help design an effective and multi-purpose future infrastructure.

3 Introduction

Today, the global navigation satellite systems (GNSS) including the U.S. global positioning system (GPS), the Russian GLONASS, the European Galileo, and the Chinese Beidou play a critical role in Earth monitoring. An accurate and reliable realization of a geodetic reference frame is crucial not only for cadastral and engineering surveying, but also for diverse scientific applications with direct societal impact, such as sea level monitoring, tropospheric water vapor content, natural hazards assessment, or infrastructure monitoring (IPCC, 2013; Raetzo et al., 2016). A modern assessment of seismic hazard requires the integration of historical and instrumental seismic data together with constraints on crustal deformation derived from geological investigations and geodetic measurements. Monitoring recent crustal movements in view of seismic hazard assessment is one of the principles behind the establishment of large permanent GNSS networks (especially in the USA and Japan) (Bock and Melgar, 2016). Due to considerably improved GNSS receiver and antenna technologies, e.g. sampling rates up to 100 samples per second (sps), and real-time processing strategies, GNSS observations are now being integrated in early warning systems for the detection and quantification of earthquakes, tsunamis, and landslides. In the last decades numerous earthquakes of magnitudes between M6.3 and M9.0 were clearly recorded by GNSS stations (Bilich et al., 2008; Larson and Miyazaki, 2008; Larson, 2009; Zhou et al., 2012; Houlié et al., 2014; Hung and Ruey-Juin, 2013; Wang et al., 2012; Yin et al., 2013; Langbein et al., 2006; Ji et al., 2004), in some cases even with sampling rates higher than the standard 1 sps (e.g. Avallone et al., 2011, 2012). As a consequence, GNSS permanent networks are becoming true multi-purpose networks. SCIGN (Southern California Integrated GPS Network), for example, combines GNSS and seismic sensors, and provides datasets ready for use in seismology (Bock and Melgar, 2016). In Europe, EUMETNET has established a similar relationship between GNSS and meteorology (Guerova et al., 2016). While sensor co-location is crucial for many applications, providing easy access to GNSS data to diverse communities is at least as important, whether through combined processing or simply by appropriate data management and exchange tools. These are major challenges for the community, and responding to them is an integral part of currently ongoing projects such as the European Plate Observing System (EPOS, www.epos-eu.org).

In the case of Switzerland, the national permanent GNSS network AGNES, operated by swisstopo as responsible institution[1], also plays an important role as multi-purpose network. In addition to the realization of the Swiss reference frame and positioning services, AGNES is an essential infrastructure for geodynamic investigations (Fig. 1). It also provides data for the so-called GNSS-meteorology research. The determination of tectonic movements by geodetic techniques contributes important information to seismic hazard assessment in Switzerland, especially in the Valais. However, given the rate of relative tectonic motion in Switzerland, the accuracy of the velocity vectors obtained from GNSS measurements that is required for geodynamic interpretations can only be reached by continuous measurements over several

[1] http://pnac.swisstopo.admin.ch/pages/en/agnes.html

years (see Sec. 5.1). This slow tectonic movement is also reflected in the moderate seismicity observed in Switzerland. In fact, the strongest earthquakes in Switzerland of the last three centuries are the events of Brig (1755), Visp (1855) and Sierre (1946), with estimated moment-magnitudes between 5.7 and 6.2 (www.seismo.ethz.ch). Nevertheless, due to the high concentration of value, Switzerland faces a significant seismic risk. This is motivation for swisstopo to increase the use of GNSS for seismic monitoring. On even smaller scales, melting permafrost in Alpine regions due to the climatic change, leading e.g. to landslides and fast moving block glaciers, requires more and more local GNSS networks for environmental monitoring with all the associated challenges.

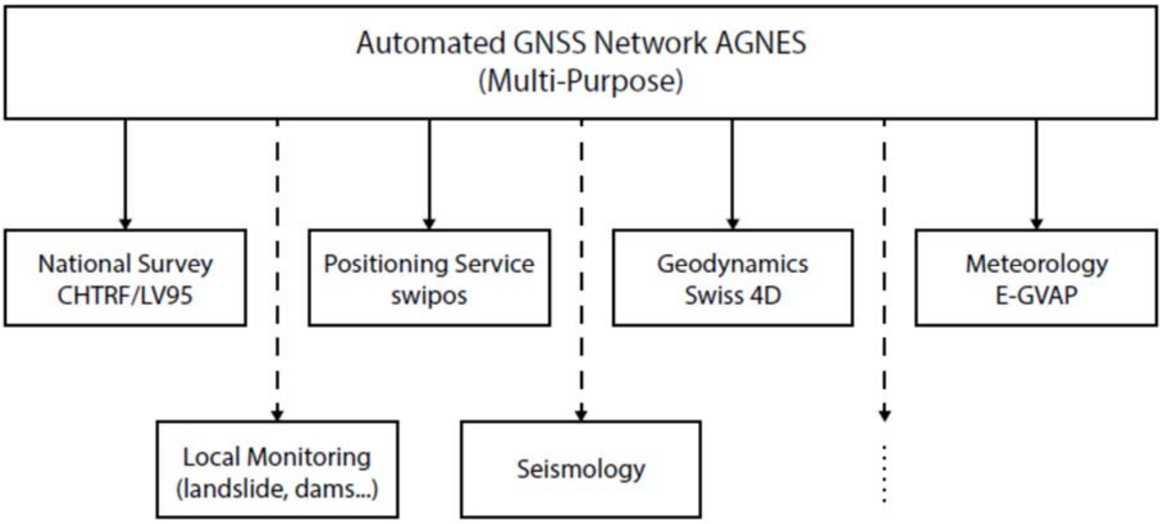

Figure 1: The automated permanent GNSS network AGNES as a multi-purpose network currently supporting applications such as national survey, positioning services (swipos), geodynamics, and meteorology. In future, AGNES might play a more important role in additional fields like local monitoring and seismology.

This growing multidisciplinary character of a permanent GNSS network fosters further cooperation inside the geodetic community as well as with other communities and disciplines such as geophysics, seismology, hydrology, physics of the atmosphere, and institutions like SED, MeteoSwiss, FOEN, WSL/SLF, and diverse cantonal offices. A wider community and the potential combination of different measurement techniques and networks pose demands on the equipment and site distribution, on unified processing strategies, data storage and dissemination tools and policies. Questions about co-locating different sensors from different networks, providing open data, and establishing denser networks are key aspects, which are not answered only by the comparison with what other countries are doing, but also by addressing the scientific rationale. Even though permanent GNSS networks provide key societal services and have clear commercial value, the focus of this document is on scientific aspects.

4 Present Situation of Networks, Instrumentation and Processing

4.1 Swiss Permanent GNSS Networks and Services

In addition to the national AGNES network, there are a number of other major permanent networks that collect GNSS data in Switzerland. This landscape is summarized in Figure 2, and each network in Switzerland is discussed below. Tables B-1 to B-2 in the Appendix B include information on the stations in each Swiss network (in particular the station codes that are mentioned in the text below).

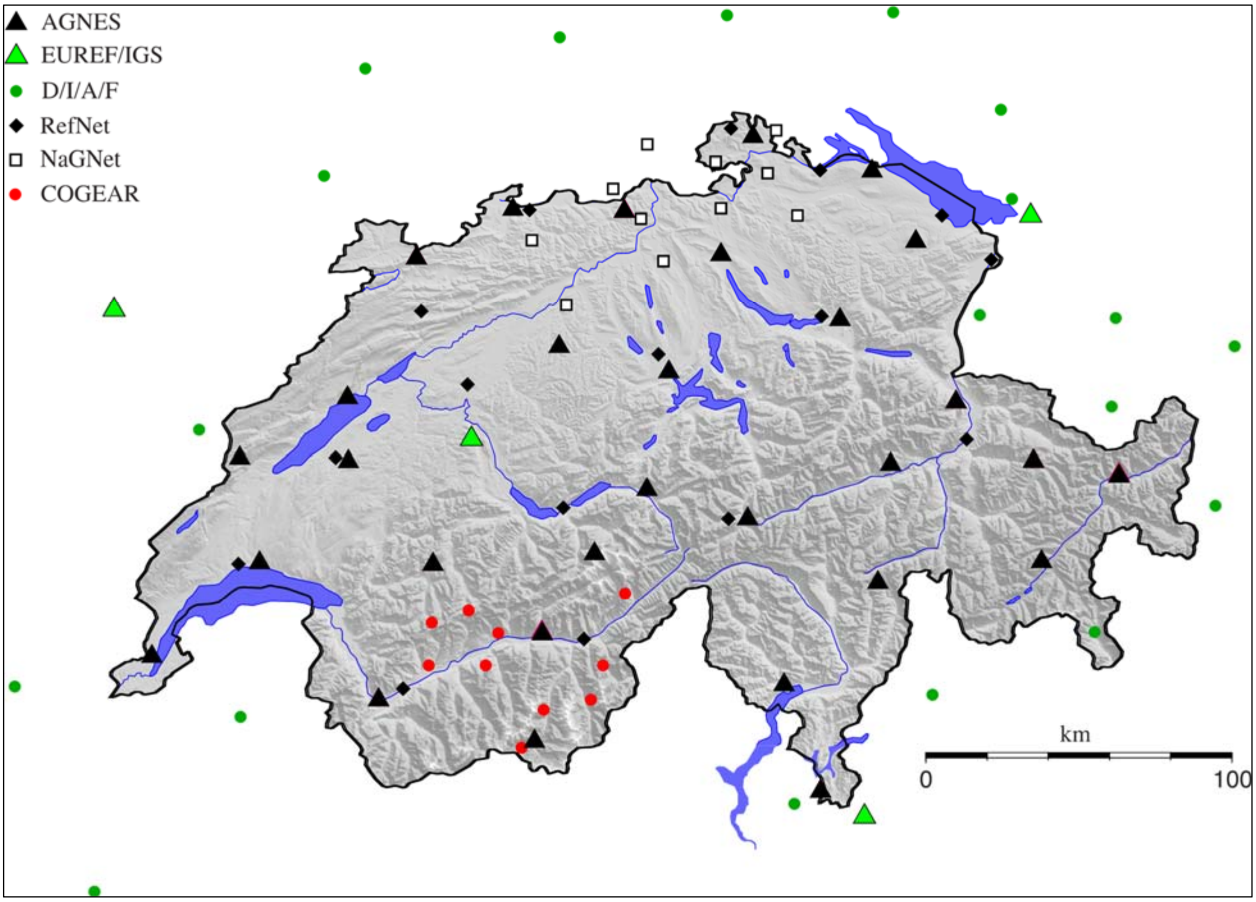

Figure 2: The present status of permanent GNSS networks and stations in Switzerland. All of these stations, with the exception of those from RefNet, are automatically processed by swisstopo. In addition to the stations inside Switzerland, data from neighboring countries are also included in the swisstopo processing.

4.1.1 AGNES and swipos

AGNES (http://pnac.swisstopo.admin.ch/index.html) is the Swiss national permanent GNSS Network operated and maintained by swisstopo in accordance with the national Geoinformation Law (GeoIG), with the core tasks of maintaining the national geodetic reference frame and providing positioning services for Switzerland. AGNES is operated as multi-purpose network for applications in national surveying, scientific applications (e.g. geodynamics) and for positioning services (Brockmann et al., 2005). 31 stations are currently available with a mean inter-station distance of 30 - 60 km (Fig. 2). 10 of these 31 AGNES stations are operated as so-called "double stations", which means that two GNSS antennas are co-located at the same station. This setup allows the internal check of accuracy and stability in case of changes in the GNSS equipment. The stations are classified in 3 classes, depending on the quality of their monumentation (Tab. B-1). Class A stations are monumented on stable rock or on massive objects with steel-masts and are suited for geodynamic studies. Class B and Class C stations are typically not installed in solid rock (sometimes even on buildings) and are therefore not suitable for geodynamic monitoring.

The following AGNES stations are co-located with stations of other measurement networks in Switzerland: the stations Frick (FRIC) and Bourrignon (BOUR) are co-located with seismic stations SULZ and BOURR of the SED, whereas the stations Geneva (AIGE), Payerne (PAYE), Samedan (SAM2), San Bernardino (SANB), Jungfraujoch (JUJ2), Locarno (LOMO and Davos (DAVO) are co-located with meteorological stations of MeteoSwiss (SwissMetNet). In addition, swisstopo operates a permanent GNSS tracking station at the rock laboratory Mont Terri that is managed by the National Geological Service at swisstopo.

All AGNES stations are equipped with high-end geodetic receivers capturing the signals of GPS, GLONASS, Beidou and Galileo on at least 2 frequencies. The stations are linked via the communication network of the Federal Administration (BV-Netz) to the control center in Bern. The observation data of the AGNES stations are streamed (1 sps) for the real-time computation of the network and the positioning services swipos. In addition, every hour complete 1-hour data files are transferred via FTP for the geodetic post-processing of the data. The data are archived at swisstopo in separate archives for the real-time data (1 sps) and the post-processing data (30 s).

The network geometry and site monuments are designed for long-term stability thus contributing to the determination of the kinematic model CHKM95 of the Swiss geodetic reference system CHTRS95 (Wiget et al., 2011). For the realization of the Swiss Terrestrial Reference Frame CHTRF, as a base for high-precision, nationwide surveying and positioning applications as well as geological studies, a much higher point density is required. For this purpose, additional well-marked points are since 1988 repeatedly measured during GNSS campaigns every 6 years (CHTRF-campaigns), see the documentation series by swisstopo on the national survey[2] . Coordinates of more than 200 points comprising this LV95 network, see Fig. 3, could provide the base for a high-density network for special applications such as so-called "task force" measurements after special geophysical events (see Sec. 5.2).

The automated processing of the AGNES network by swisstopo combines the AGNES stations with stations from other local networks (see Secs. 4.1.2 and 4.1.3) as well as from neighboring countries. The processing includes monitoring of the current network performance and produces different outputs, e.g., velocity fields usable for geodynamics (see Sec. 5.1 and Wiget et al., 1991), and zenith total delays (ZTDs) for meteorological applications (see Sec. 5.2). The processing is done by the Permanent Network Analysis Center (PNAC) at swisstopo using the Bernese GNSS Software (Dach et al., 2015). This a scientific, high-performance and high-

[2] https://shop.swisstopo.admin.ch/de/products/publications/geodesy/swisstopo_doku_pdf

precision multi-GNSS data post-processing software package developed at the Astronomical Institute of the University of Bern (AIUB). It is widely used around the world, for example by CODE (Center for Orbit Determination in Europe) for its international (IGS) and European (EUREF/EPN) activities. Characteristics of the Bernese GNSS Software are state-of-the-art modeling, detailed control over all relevant processing options, powerful tools for automatization, the adherence to up-to-date, internationally adopted standards, and the inherent flexibility due to a highly modular design. However, it currently does not have real-time capabilities.

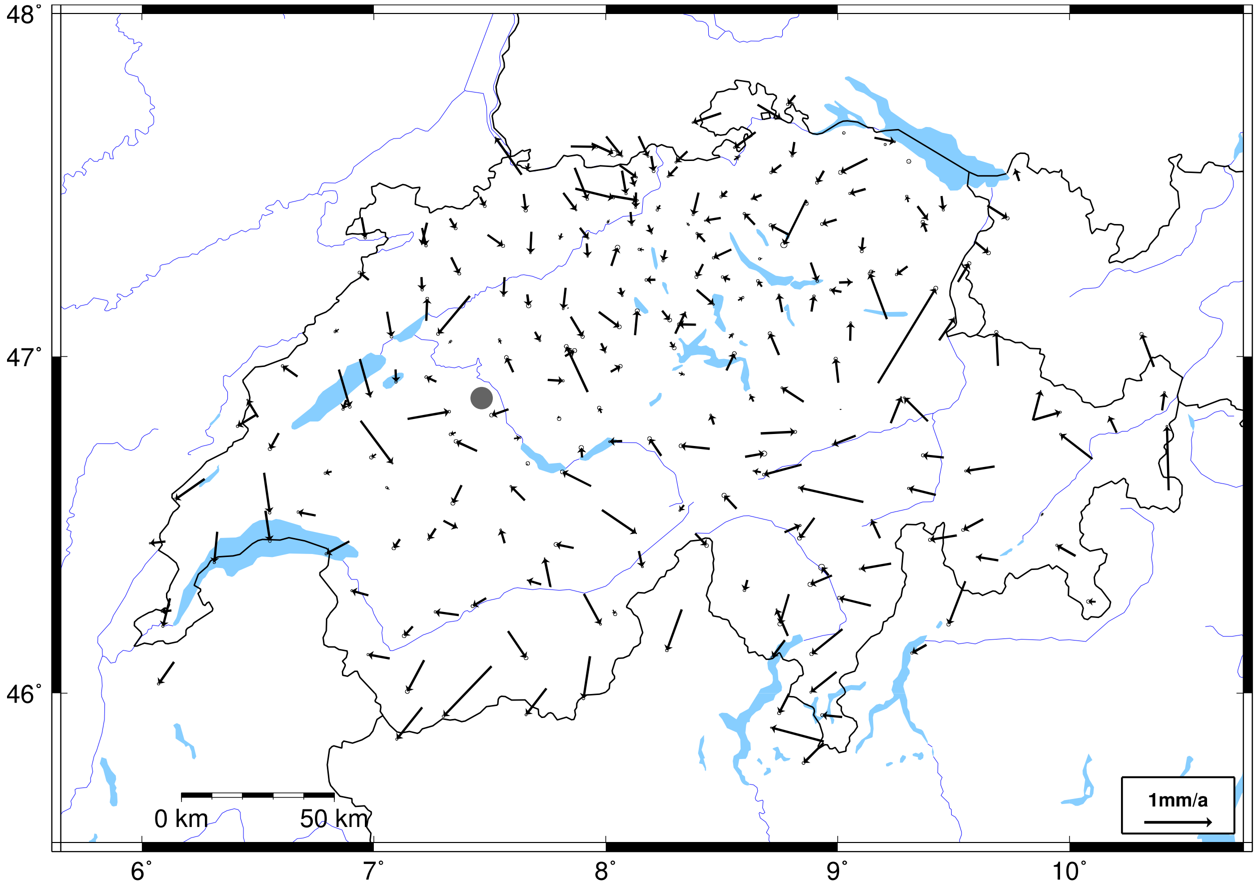

Figure 3: Velocities of the LV95 network relative to the station Zimmerwald shown as grey circle, computed from all LV95/CHTRF-campaigns up to CHTRF2010 (swisstopo) (Villiger, 2014a).

AGNES also provides the base network for the currently four swipos real-time positioning services (Tab. 1). In particular, the swipos-GIS/GEO[3] service is an important service for the cadastral surveying, as it enables fast and reliable positioning at centimeter level. Other applications are engineering geodesy and monitoring, construction and machine guidance, agriculture and precision farming. swipos-GIS/GEO, based on the virtual reference station (VRS) concept, allows a single baseline real-time kinematic (RTK) positioning that only requires an RTK engine in the receiver. The swipos-INFRA service requires an external real-time software (e.g. open source software RTK-Lib) that is able to process network solutions.

[3] https://shop.swisstopo.admin.ch/de/products/geoservice/swipos/swipos_GISGEO

In order to improve the VRS interpolation accuracy for the positioning services, nationwide permanent GNSS stations of the neighboring countries are integrated in the real-time computation of the network.

	NAV	**GIS/GEO**	**INFRA**	**swipos-PP**
Availability	real-time	real-time	real-time	post-processing
Technique of processing	Code differencing	Code & Phase differencing	Code & Phase differencing	Code & Phase differencing
Baseline or network type	Single-baseline	VRS Single-baseline	Single baseline	Network
Software	onboard	RTK onboard	external RTK	PP software
Multi-GNSS	Y	Y	Y	Y
Accuracy	0.3 – 1.5 m	0.01 - 0.03 m	0.01 - 0.03 m	< 0.01 – 0.02 m
Max. samp. rate	1 sps	1 sps	1 sps	1 sps
Protocol	Ntrip	Ntrip	Ntrip	FTP / Mail
Format	RTCM 2.3	RTCM 3.1	RTCM 3.1	RINEX

Table 1: The four swipos services based on the AGNES network, see text for further explanations. swipos-NAV requires a receiver capable of differential code processing, but with an accuracy of about 0.5m it does not reach the accuracy needed (< 0.01 m) for the applications discussed in this paper. swipos-PP is the post-processing service.

4.1.2 NaGNet

The National Cooperative for the Disposal of Radioactive Waste (Nagra, www.nagra.ch) is the technical competence centre in the field of deep geological disposal of radioactive waste in Switzerland. The site selection process for the construction of safe geological repositories for all radioactive waste requires a well-known geology and monitoring of the geodynamics. For this purpose Nagra installed in 2011 a dense network of 11 permanent high-quality GNSS stations in northern Switzerland (NaGNet, Fig. 2). All NaGNet stations are online (internet access) and fully integrated into the automated processing and permanent archive of swisstopo, though Nagra is responsible for station operations and data acquisition. For integration in PNAC, data is downloaded (via FTP), processed and archived with a sampling of 30 s, even though the receivers are acquiring the data with a sampling rate of 10 sps (on-site ring buffer of about 10 days). This high-rate data can be made available for scientific studies. An agreement is already in place between Nagra and SED for the rapid retrieval of high-rate data after a significant earthquake.

4.1.3 Local GNSS Networks

Another specific densification of the permanent GNSS networks has been achieved in the Canton of Valais as part of the COGEAR project (Fäh et al., 2012). This region, with one of the highest levels of seismicity in Switzerland, was chosen in order to investigate the ongoing geophysical processes across a range of observables (seismology, geodesy, geology, geochemistry). The sites for the 10 GNSS stations installed by IGP, ETH Zurich (red circles in Fig. 2) were selected to span the region, where increased deformation may occur, with co-location alongside existing seismic instruments of the SED where possible. Co-located stations were established at Fiescheralp (FIES), Simplon (SIMP), and Sanetsch (SANE). All COGEAR stations are online (internet access) with a maximum sampling rate between 1 sps and 20 sps (ring buffer) and track at least GPS dual-frequency signals since 2005 and 2006 (already installed during a previous project TECVAL) and 2011-2014 (Villiger, 2014b). Table B2 in the Appendix provides details, including the equipment installed. The stations are currently maintained by IGP that daily downloads and stores RINEX files with 30 s sampling of each station on an IGP ftp server. From there the files are downloaded by swisstopo for automated processing and permanent archiving. The inclusion of NaGNet and COGEAR in the harmonized processing by swisstopo (see Fig. 2) is an important step towards routine combination of GNSS data from different networks. The potential real-time accessibility of GNSS data depends on the available infrastructure. The data with highest sampling of 20 sps (even 100 sps at Fiescheralp) are only stored in an on-site ring buffer (at least 10 days buffer size) and retrievable for post-processing, e.g., after seismic events. However, there is currently no assigned responsibility and/or automated procedure for downloading these data after an event.

Additional permanent GNSS sites, focusing on geomonitoring and natural hazards, have been installed in specific regions in Switzerland. These small networks are operated by institutions or private companies, though the Federal Office for the Environment (FOEN/BAFU) is strongly involved. Currently, only few such stations provide data for open access. Typically, they are equipped with low-cost receivers and antennas (only L1) and are not included into the swisstopo processing. Potential future long-term archiving of such data by swisstopo remains to be decided and specified.

4.1.4 RefNet

RefNet (www.refnet.ch) is a private permanent GNSS network maintained by several companies in order to provide positioning services for cadastral surveying, engineering geodesy, local monitoring, machine guidance and other applications. Currently 17 stations are available in Switzerland and two in the neighboring countries Germany and France, see Fig. 2. In the near future, the installation of additional sites is planned in the region of Geneva, Ticino, and South Grisons. The standard equipment are dual-frequency GNSS receivers. The service provided is similar to the swipos-GIS/GEO of AGNES with the difference of sending network corrections without using a VRS. All reference station data are archived and are available for download for post-processing applications. The streaming of real-time observations (like swipos service INFRA) is currently not provided, but could be generally realized based on the available infrastructure. In contrast to the AGNES network, RefNet is purely commercial and the exchange of open data for a nationwide GNSS geomonitoring and data archiving is not expected in the near future.

4.2 International Permanent GNSS Networks and Services

This section presents an overview of some specific GNSS networks with their infrastructure and services focusing on neighboring countries and the U.S. Real-time GNSS networks that begin to be embedded in earthquake early warning systems are also operated in other countries such as Japan or Chile, but are not further discussed here.

4.2.1 Permanent GNSS Networks and Services of Neighboring Countries

In Germany GREF[4] (Integriertes Geodätisches Referenznetz), operated by the BKG (Bundesamt für Kartographie und Geodäsie), and SAPOS[5], under the responsibility of 16 state surveys, are the official providers of the national reference frame. SAPOS provides services for governmental and commercial users such as network solutions for all Germany in real-time (see Tab. 2). SAPOS comprises more than 270 permanent sites operated by the German state surveys (Fig. 4), and is complimented by nearby stations in neighboring countries. The inter-site distances are comparable to those of the AGNES network and to those of other neighboring countries such as Italy (SmartNet ItalPoS with about 150 stations), France (TERIA with about 200 stations), Austria (APOS with 43 stations), and other European countries. Each state survey provides three different SAPOS services, very similar to the swipos services using the AGNES network (see Sec. 4.1.1 and Tab. 1). One central office (Landesamt für Geoinformation und Landesvermessung Niedersachsen) is additionally responsible for the coordination between all the state surveys and for the entire quality management. Other national services from neighboring countries - ItalPos[6], TERIA[7], and APOS[8] - also enable RTK applications via Ntrip based on VRS sending RTCM 3.x messages. The RINEX files are also available and accessible via a web interface for post-processing applications. In most cases, external users may access the data against payment. The services of these different countries are mainly commercially driven and do not provide open data sets. The networks are often mixed with stations of the state surveys, stations operated by scientific institutions (e.g. some RING stations, see Sec. 4.2.4, are included in SmartNet ItalPoS), and private companies. For instance, the Austrian BEV (Bundesamt für Eich- und Vermessungswesen) is responsible for the Austrian GNSS network consisting of stations operated by the BEV, by the Austrian Academy of Sciences, by the Leopold-Franzens-University of Innsbruck (LFUI) and by Kelag, one of the leading energy service providers in Austria. In France the TERIA network is partially based on the stations of the RGP (Réseau GNSS Permanent) which is operated by the IGN (Institut National de l'Information Géographique et Forestrière).

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[4] https://gref.bkg.bund.de
[5] http://www.sapos.de
[6] http://it.smartnet-eu.com
[7] http://www.reseau-teria.com
[8] http://www.bev.gv.at/portal

	EPS	HEPS	GPPS
Availability	real-time	real-time	real-time
GNSS	GPS/GLONAS	GPS/GLONAS	GPS/GLONAS
Accuracy	0.3 – 1.5 m	0.01 - 0.03 m	< 0.01 - 0.02 m
Max. samp. Rate	1 sps	1 sps	1 sps
Protocol	Ntrip	Ntrip	Web interface
Format	RTCM 2.1	RTCM 2.1/3.1	RINEX

Table 2: The three services provided by SAPOS (SAPOS, 2015), which are similar to those of swipos, ItalPoS, TERIA, and APOS. EPS: Echtzeit Positionierungsservice; HEPS: Hochpräziser Echtzeit Positionierungsservice; GPPS: Geodätischer Postprocessing Positionierungsservice.

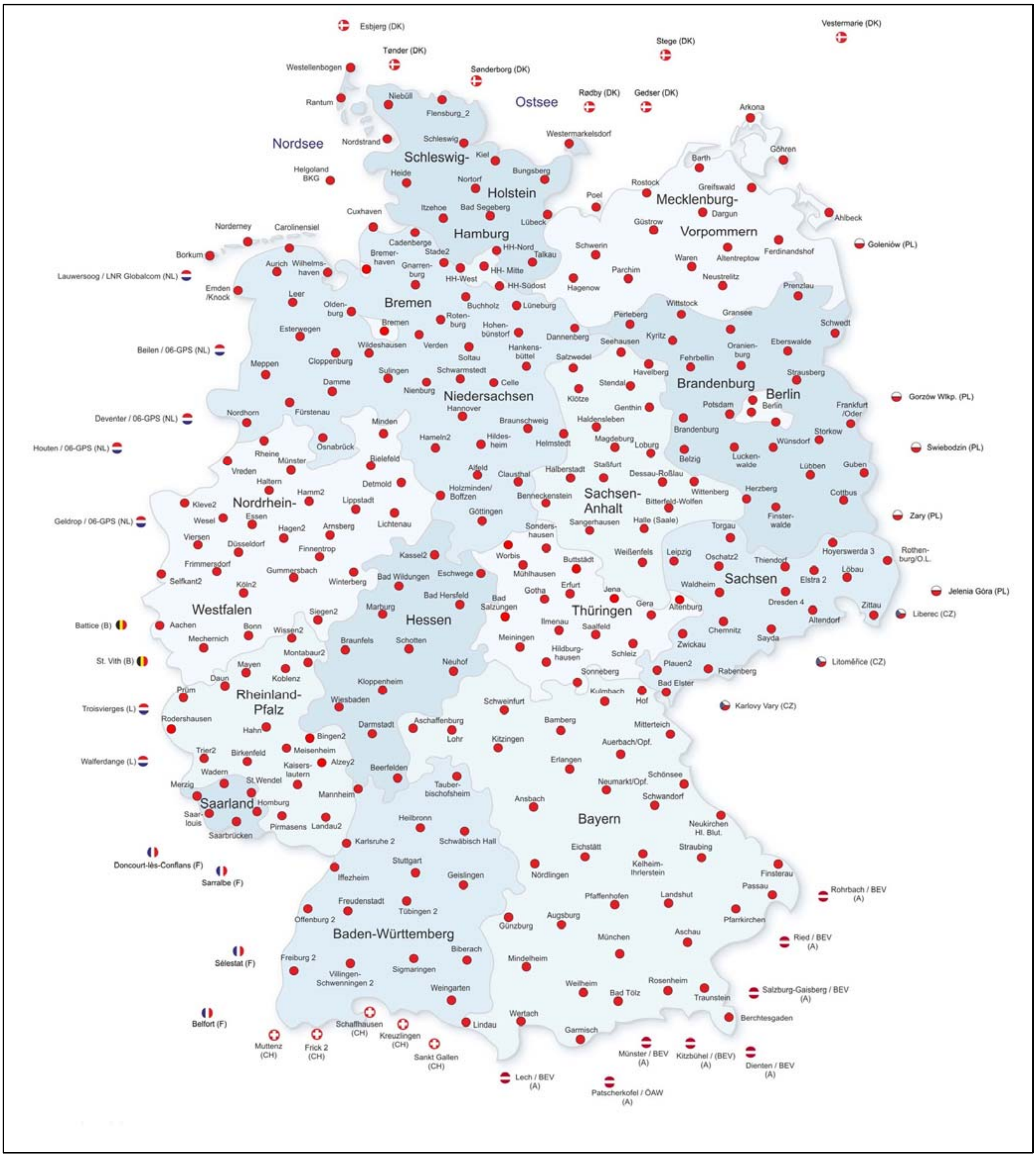

Figure 4: GNSS stations that contribute to SAPOS. Sites in Germany are illustrated by red dots, flags represent stations operated by neighboring countries.

4.2.2 EUREF/EPN and IGS

The European Permanent Network (EPN) is the EUREF (European IAG subcommission; www.euref.eu/) permanent GNSS network providing fundamental geodetic measurements for Earth science applications in Europe (Ihde et al., 2014; www.epncb.eu). About 250 stations comprise the network (Fig. 5) providing near real-time and real-time GNSS data for the realization of the European Terrestrial Reference System (ETRS89, http://etrs98.ensg.ign.fr). The EPN stations represent a densification of the global GNSS network of the International GNSS Service (IGS, www.igs.org) and are an integral part of the realization of the International Terrestrial Reference System (ITRS, http://itrf.ign.fr). In addition to the ITRS/ETRS station positions and velocities, different products are provided such as tropospheric zenith path delays, precise satellite orbits and clock corrections. These products are generally used for scientific purposes such as geodynamics and meteorology and cover the same applications as described in Sec. 4.3 for the whole of Europe. The global IGS network consists of about 450 stations (150 real-time stations), all fulfilling the defined high-quality IGS standards (IGS, 2015). A single AGNES station, Zimmerwald, is part of the EPN and the IGS network and directly connected to the international and European reference frames and height systems.

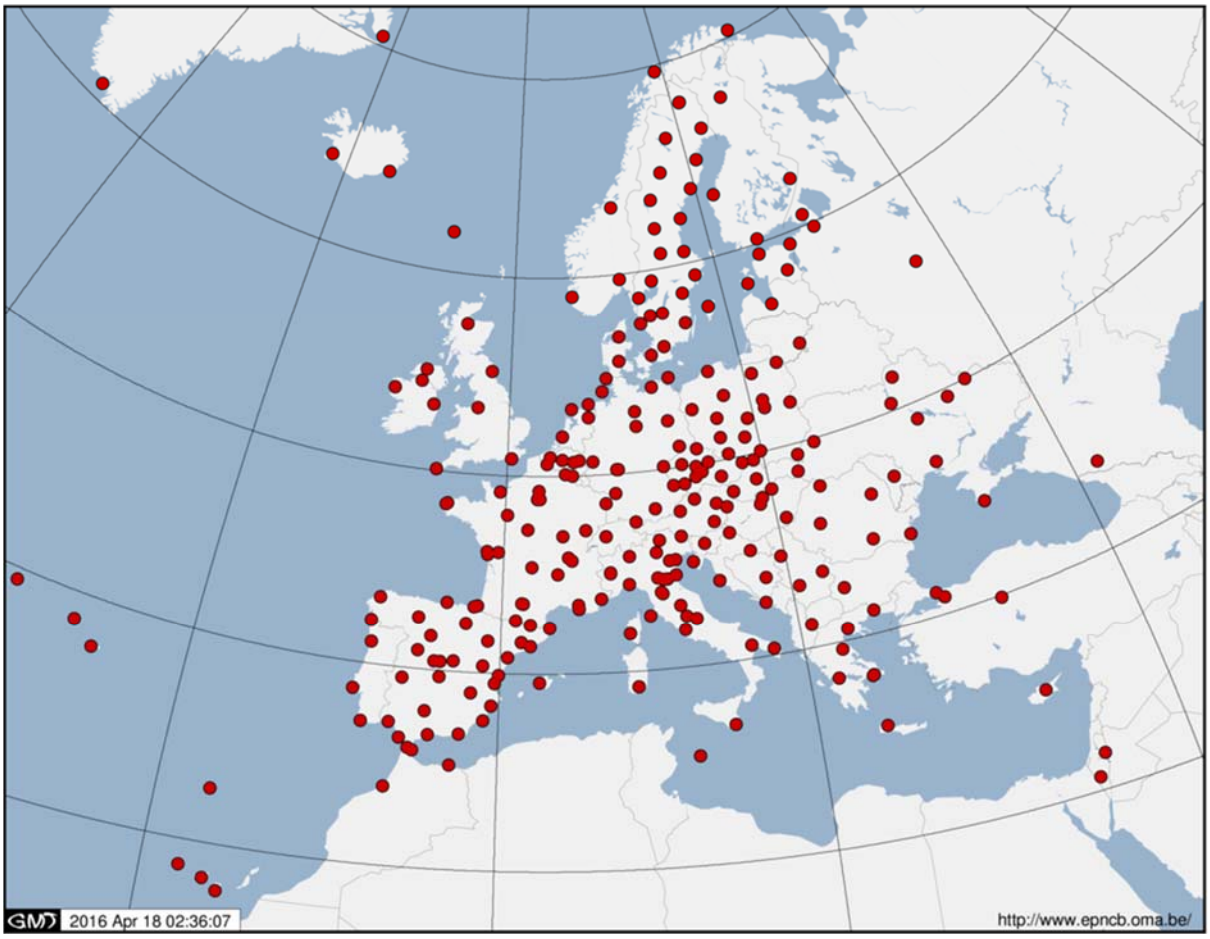

Figure 5: The EUREF permanent GNSS network EPN with all available tracking stations.

The data of the IGS and EPN stations are collected in several data centers around the globe (10 IGS data centers and 9 EPN data centers). The analysis centers process all the available data or subsets in parallel and independently from each other. Various analysis centers provide their products to the analysis center coordinator for the combination leading to the final products, all open data. The observation data of the tracking stations are available through the data centers as daily and hourly RINEX files with 30 s sampling. Real-time observation data and products are also available in the RTCM format (http://www.epncb.oma.be/_networkdata/).

swisstopo acts as a local analysis center (LAC) for EUREF and is also member of the CODE (Center for Orbit Determination in Europe) consortium. Within these activities swisstopo closely cooperates with the Astronomical Institute of the University of Bern (AIUB).

4.2.3 European Plate Observing System - EPOS

The goal of EPOS (European Plate Observing System, www.epos-eu.org) is to establish a multidisciplinary solid Earth research infrastructure in Europe, aiming at an integrated use of data, models, services and software, provided by existing and new infrastructures in different research fields of solid Earth science (e.g., seismology, volcanology, geodesy, geology, ...). Emphasis is put on providing easy cross-disciplinary access to open data and products using standard services. None of the Swiss GNSS networks is integrated into EPOS up to now.

The EPOS GNSS section focuses on building a joint European GNSS data and product distribution system into which not only EPN contributes, but also the large number of stations from national and academic networks. In addition to the exchange of raw observation data in RINEX format, products derived from a combined processing should be delivered in future, such as site coordinates, time series, velocities, strain rate maps, and metadata. Currently one main activity addresses the development of a new concept for GNSS data management including metadata inventory, file downloads and feedback on data quality and availability (Fernandes et al., 2016), based on and expanding upon existing UNAVCO standards (see Sec. 4.2.5). After the definition of metadata standards, the design of relevant database structures and interfaces to data providers and users, the development and testing of the integrated GNSS data dissemination infrastructure will proceed in the next years.

4.2.4 Italian Co-located GNSS network RING

The Italian network RING (Rete Integrata Nazionale GPS) is operated by the National Institute of Geophysics and Volcanology and aims at a better understanding of the complex kinematics of a variety of microplates in the convergence across the Western Mediterranean (Avallone et al., 2010). The network is composed of about 180 high-end GNSS stations. The concentration on Southern Italy and Sicily leads to a station spacing in the order of 20 - 25 km in some target regions (http://ring.gm.ingv.it). Diverse key stations are equipped with co-located broad-band seismometers and accelerometers in order to monitor the frequency content of the earthquake process (Avallone et al., 2011). High-quality monuments designed for long-term stability are a key feature of the network. Comparable to the standard “Short Drilled-Braced" monument of the SCIGN (see Sec. 4.2.5), a so-called “shallow drilled braced" monument has been developed for a simplified installation of a screwed tripod and for improved grip inside the soil. Beside the shallow braced tripods, concrete pillars are anchored with four lateral rods 1 meter down in the ground. Where bad geological conditions require it, deep installations of about 10 meters are realized. The RING stations are connected in real-time to three acquisition centers located in Rome, Grottaminarda, and Catania. Some stations transmit their data via VSAT (Very Small Aperture Terminal) links with 30 s sampling, others have internet connection allowing a real-time data streaming of 1 sps. The low power consumption of the satellite transmission allows the operation of the field stations with solar panels. The RINEX observation files and metadata of the RING are centrally managed and stored in a relational database. The RINEX files and the corresponding screening information (data availability, gaps, and other station parameters) are openly available via an ftp server[9].

No routine combined processing of seismic and GNSS data is performed. The main product based on GNSS data of the RING network (and some external reference sites) is a velocity field represented by daily station coordinates. Processing is achieved by the three main scientific GNSS software packages Bernese, GAMIT, and GIPSY-OASIS in parallel, being combined into a final solution.

In comparison with Switzerland, the RING network stands out with regard to its standardized high-quality monumentation, targeted co-location with seismic equipment, redundant processing centers, and open access to (raw) data.

4.2.5 UNAVCO and U.S. Plate Boundary Observatory

UNAVCO (www.unavco.org) is a non-profit university-governed consortium in the US with a mission to facilitate geoscience research and education using geodesy. UNAVCO collaborates with other institutions on a variety of projects and provides solutions in the scope of monumentation and operation of geoscience sensors such as GNSS, meteorological units, LiDAR for TLS, or borehole instrumentation (e.g. strainmeters, tiltmeters, borehole pressure). An exhaustive knowledge base is available (kb.unavco.org/kb/) with e.g. information on different types of monuments and sensors and the specific communication solutions for different bandwidths and power consumptions. One single data center collects all the data from thousands of globally distributed permanent GNSS stations and provides them as daily raw files, converted RINEX files and final products such as positions, velocities and ZTDs (or integrated precipitable water vapor (PWV) for sites co-located with meteorological stations) with a sampling of 15 s or 30 s. High-rate data of 1 sps and higher as well as real-time data streams (of a subset of stations) are available, too. In addition to the highly sophisticated post-processing GNSS software packages like Bernese, GIPSY and GAMIT, real-time software packages such as RTKLib and RTNet are involved in the processing chain. The data and analysis center is completely science-driven, which simplifies the promotion of an open data

[9] ftp://gpsfree.gm.ingv.it/OUTGOING/RINEX30/RING/

policy, not only for GNSS data sets, but also for strain and seismic data, imaging and tropospheric data. All the data sets, products and metadata are permanently archived at UNAVCO and are freely available via a web interface[10].

The PBO (Plate Boundary Observatory, http://pbo.unavco.org/) is a component of the EarthScope project (www.earthscope.org), a major US NSF-sponsored project in which UNAVCO is involved. The main objective of the PBO is the quantification of the deformation and temporal variability across the North American plate. The measurement techniques and networks consist of 1100 permanent (at least for the duration of the project) and continuously operating GPS stations, 74 borehole strainmeters (BSM) and 78 short-period borehole seismometers comprising the PBO BSM Network and the PBO Borehole Seismic Network, respectively[11]. Finally, PBO installed very long-baseline surface laser strainmeters (LSM) and took over the operation and maintenance of one legacy station that was built to similar specifications as the six LSMs now making up the PBO LSM Network. Additional GPS sites in Southern California were integrated into the PBO through UNAVCO building a dense network with 250 continuously operating GPS stations, the so-called SCIGN (Southern California Integrated GPS Network). In cooperation with operators such as the US Geological Survey (USGS), the NASA Jet Propulsion Laboratory (JPL), and other agencies, this network defines the state-of-the-art with respect to the integration of GNSS into earthquake early warning (EEW) systems, and to the combined real-time processing, single data center, data archiving, real-time data exchange, and open data policy. The USGS operates the real-time network using a commercial software package RTNet and the integrated Trimble solution RTX, both based on PPP processing. Key aspects of real-time PPP processing are the required correction data (orbit and satellite clocks) with a small data latency. For a further latency minimization of the commercially provided correction streams, the USGS currently computes its own correction data based on the observations of its own network and reduces the latency down to 1 s. Data products for various US permanent and campaign networks are provided by the USGS[12].

Key lessons that can be learnt from this network when compared to the situation in Switzerland are the implementation of an open data policy, high-quality access services, high sampling rates, low latency data access and processing, and the use of the network to drive novel science and software.

10 https://www.unavco.org/data/gps-gnss/gps- gnss.html

11 http://www.unavco.org/instrumentation/networks/status/pbo

12 http://earthquake.usgs.gov/monitoring/deformation/

4.3 Summary and Conclusions

- The spatial distribution, density, and infrastructure (multi-GNSS) of the AGNES network are comparable to other European countries. The current hardware is modern and trends toward densification are ongoing. However, the monumentation of the AGNES stations is not of uniformly high standard, as has already been realized by the Italian RING or the U.S. SCIGN network.

- Specific densifications exist in northern Switzerland (NaGNet) and in the Canton of Valais, a seismogenic region covered by the COGEAR network. Both networks are integrated into the automated processing by swisstopo (30 s data). All stations acquire multi-GNSS data with 10-20 sps. The high-rate data is stored in a ring buffer for about 14 days and is available for download. Central and long-term data archiving of the low- and high-rate data of these networks is not established yet at swisstopo. There is a trend towards of fragmentation in the community in Switzerland, with multiple operators that have no clear responsibility to provide data to AGNES. Additionally, data collected is of heterogeneous quality.

- Co-location of GNSS stations with other measurement equipment is almost unrealized for Swiss GNSS networks (e.g., seismometer, boreholes...), in contrast to many European and U.S. networks. Today, only three stations of the COGEAR network and two from AGNES are co-located with broadband and strong motion seismic sensors, and seven with the MeteoSwiss Network.

- The 200 points of the campaign network LV95 are routinely re-measured by swisstopo every 6 years, though this is a best effort with no clear requirement or funding.

- The positioning services (swipos) provided by swisstopo are comparable to those of neighboring countries. The existing infrastructure of all AGNES stations allow real-time data streaming with 1 sps (swipos-INFRA). Real-time observation data streams from NaGNet and COGEAR stations are not established. At swisstopo real-time data processing only exists for the swipos positioning service (network solution and computation of VRS). All geodetic processing is done with the Bernese GNSS software as post-processing (i.e. no real-time capability yet). A migration to routine and real-time streaming of higher rate sample rates is technically possible at reasonable expense.

- No standardized data exchange formats and dissemination tools for processed GNSS time series exist between different communities, however, efforts are under way within EPOS (coordination on European and international level). The automated dissemination of raw AGNES data (RTCM) is possible over the swipos-INFRA service.

Network	Scale	Stations	Co-location	Real-time	Data centers	Open Data
AGNES	national (CH)	31	rarely	1 sps	1	(yes)
NaGNet	local	11	no	no	1	no
COGEAR	local	10	partly	no	1	(yes)
SAPOS	national (DE)	270	no	1 sps	15	no
ItalPoS	national IT	150	no	1 sps	1	no
TERIA/RGP	national (FR)	200	no	1 sps	1	no
APOS	national (AT)	43	no	1 sps	1	no
RING	national (IT)	180	yes	30 s – 1 sps	3	yes
EPN	continental	250	no	no	9	yes
PBO/SCIGN	regional	1100/250	yes	1 sps (some)	1	yes
IGS	global	450	no	1 sps (some)	10	yes

Table 3: Overview of the GNSS networks described in Chapter 4.

5 GNSS-based Geomonitoring in Switzerland

In addition to national survey and positioning services (swipos), swisstopo also uses the Bernese GNSS software for automated processing of the AGNES, NaGNet, COGEAR and selected stations from neighboring countries. This system includes monitoring the current network performance and produces different outputs, e.g., velocity fields usable for geodynamics (Sec. 5.1), and zenith total delays (ZTDs) for meteorological applications (Sec. 5.2). The results are presented on the swisstopo data web-portal.

5.1 Geodynamics: Swiss 4D/COGEAR

Swiss-4D I and II were two research projects initiated and funded by swisstopo, focusing on the detection of tectonic movements in Switzerland, especially the Swiss intra-plate deformation using CHTRF. Based on geodetic techniques, the main challenge is the separation of local effects from tectonic motions due to the extremely small intra-plate deformations of below 1 mm/year. For the determination of the tectonic deformation and strain not only the site velocities from the AGNES stations are included, but also the LV95 network (more than 200 points, Fig. 3) in order to increase the spatial resolution as well as leveling data to enhance the information and accuracy of the vertical movements. The strain rate field derived from GNSS campaigns for CHTRF leads to a realistic solution for the ongoing tectonic processes (Fig. 6). The COGEAR[13] network has been installed in order to enhance the coverage of the seismogenic region in the Valais by continuous GNSS data (see Sec. 4.1.3). In the Canton of Valais, an extension of the length of the time series is needed to improve the knowledge of tectonic deformation. This holds true in general for all of the long-term deformation measurements (Villiger, 2014a).

Nevertheless, the existing data sets show strain rates that amount to 25 μm/km per year (Villiger, 2014a). Relative to the reference station Zimmerwald, the velocity field shows the following characteristics: 1) The horizontal velocities are between zero and 1 mm/yr. 2) The western part of the Swiss Molasse Basin is moving towards South-West (0.3 mm/yr). 3) The southern part of the Canton of Grisons is moving westward (0.5 mm/yr). 4) The Southern region of the Rhone valley is moving towards South-West (1 mm/yr). 5) The uplift rates are zero mm/yr for the Swiss Molasse Basin and increase to 1.5 mm/yr in the Swiss Alps with peaks in the Cantons of Valais and Grisons.

[13] http://www.mpg.igp.ethz.ch/research/geomonitoring/cogear-gnss-monitoring.html

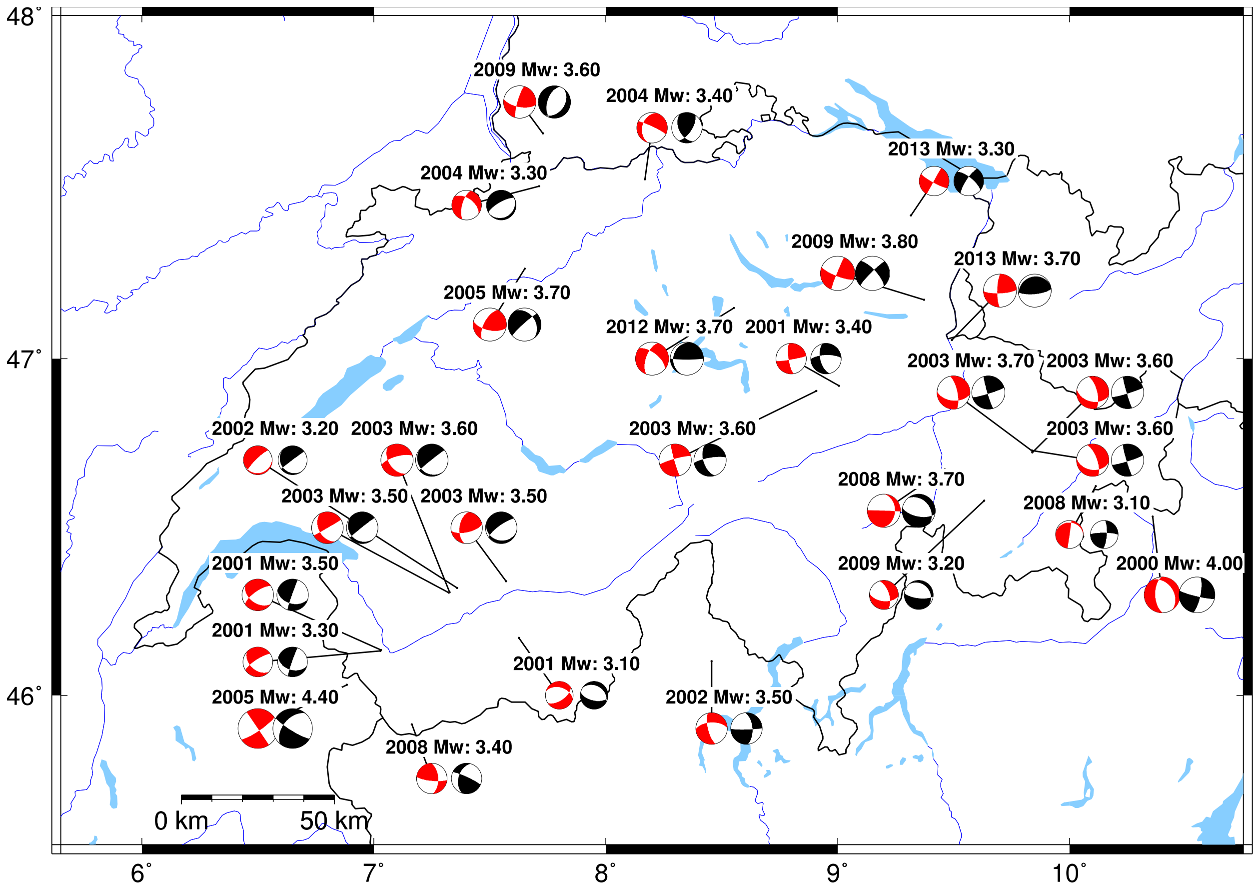

Figure 6: Beachball representations of moment tensor solutions derived from the 3-D strain rate tensor (red) compared to the earthquake solutions between 2004 and 2013 above M3.4 from seismic recordings (SED, black) (Villiger, 2014a).

5.2 Meteorology

The estimated ZTDs (an output of the automated processing by swisstopo) for each AGNES station with a temporal resolution of one hour are provided to MeteoSwiss and EUMETNET, a grouping of 31 National Meteorological Services in Europe. The meteorological data derived from more than 500 GNSS stations across Europe are an integral part of diverse projects (e.g. E-GVAP EUMETNET EIG GNSS water vapour programme) and services of the European Centre for Medium-Range Weather Forecasts (ECMWF, www.ecmwf.int) that serve to enhance their forecasting capabilities.

GNSS meteorology in Switzerland mainly is based on the works of Troller (2004) and Perler (2012) using a technique called GNSS tomography, providing tropospheric water vapor content with high spatial and temporal resolution. Most of the investigations presented in Perler (2012) are based on the existing operational setup using GNSS measurements from the AGNES receiver network. Assessing the impact on the formal accuracy of the tomographic results achievable with technical improvements in the observational data, such as additional receiver stations, station location optimization, and adding other GNSS, revealed that receiver stations should be placed at different altitudes whenever possible, and at locations where satellites are visible down to low elevations. The accuracy is mainly improved in the lower 4 km of the troposphere. An extension of the AGNES network with additional receiver stations at the locations of the permanent MeteoSwiss network SwissMetNet (SMN) stations, increasing the number of receiver stations from 31 to 91, would lead to an improvement of about 20% in formal accuracy. The use of the additional GNSS Galileo would improve the formal accuracy by about 10-15%.

The potential of GNSS tomography in spatially dense GNSS networks was investigated by Hurter (2014) using data from a campaign in Zermatt with inter-station distances of 1-2 km. The Zermatt campaign data from 34 GNSS stations yields ZTD values from PPP that reach standard deviations of 4-6 mm with respect to radiosonde measurements. The radiosondes' profiling nature is shown to miss some of the horizontal variability. Zenith-pathdelays depend on their position of calculation. The horizontal variability of a few millimeters of zenith-pathdelays is present at scales of roughly 5 km. Consequently, the standard deviations of the campaign's ZTDs are likely to be < 5 mm. This represents about less then 3 per mill of the total path delay, which in the corresponding research area is about 1.8 m. It is also demonstrated that ZTDs catch horizontal spatial variabilities down to a few kilometers, this however requires a very dense GNSS network which is referenced to the AGNES network.

In contrast to France (Poli et al., 2007), U.K. (Bennitt and Jupp, 2012), and other European countries, ground-based ZTDs derived from GNSS measurements are not yet integrated into the weather models by MeteoSwiss. In future, however, it is expected that slant delays will directly be assimilated into weather models (Deng et al., 2011; Bauer et al., 2010), rather than GNSS tomography-derived water vapor content. The required densification and co-location of GNSS and meteorological sensors (temperature, pressure) could be achieved by equipping selected SMN stations with GNSS receivers and antennas, and a combined processing with AGNES/EPN.

5.3 Monitoring of dams, glaciers, block glaciers, landslides

Driven also by the increased availability of low-cost equipment, GNSS becomes an increasingly valuable tool for the monitoring of local natural hazards and critical infrastructures. Most of these networks consist of few stations only, deployed with small inter-station spacing over a small area. The main infrastructure challenges of such networks, often located in difficult environments (alpine regions such as glaciers, block glaciers, hillsides), are power and communication. Further, the usage of low-cost receivers that track only L1 requires a small inter-station distance (max. few kilometers) to minimize the ionospheric influence and thus the usage of ionospheric models as well as a nearby reference station with at least dual-frequency equipment for a correct connection to a reference network. To allow a better long-term interpretation of regional tectonic movements as well as for their combination in other applications, all local networks in Switzerland should be connected to the same common geodetic reference frame provided by the AGNES network. Therefore, a dense AGNES network in the regions of interest can improve the important connection of local monitoring networks to the Swiss reference frame (CHTRF/LV95). The Federal Institute for the Environment (FOEN/BAFU) is heavily involved in several projects and is interested in the monitoring of diverse natural phenomena (e.g. landslides, permafrost). Point velocities are typically estimated based on a daily processing. Tests of GNSS real-time applications with low-cost receivers were recently a topic in the project Xsense (Nano-Tera Program of Swiss National Foundation), where several stations were equipped with a special low-power communication system (Beutel et al., 2011, Limpach et al., 2011).

5.4 Summary and Conclusions

- Geodynamic applications require long-term measurements and highest stability of the monumentation due to extremely small tectonic movements in Switzerland, while sampling rate and real-time accessibility are not critical. High spatial resolution is needed, however, as demonstrated by the latest research based on a velocity field derived from more than 200 points of the LV95 network in Switzerland (CHTRF).

- Processed ZTDs from all AGNES stations are made available through E-GVAP to the interested European institutions. The spatial resolution of the AGNES stations is already the highest of the EUMETNET countries in central Europe. The temporal resolution of 1 hour is sufficient for the ZTDs. The hourly post-processing is based on 30 s GNSS data. However, local meteorology using tomography requires a higher spatial density and stations at different elevations (also of interest for extreme events). The processing is based on PPP or double-differences. In contrast to neighboring countries, ZTDs are not assimilated into the numerical weather models of MeteoSwiss, and only few stations of the SwissMetNet are equipped with GNSS sensors.

- Local monitoring networks often consist of L1-only measurement equipment. For the connection to the common national reference frame (AGNES realizing CHTRF/LV95) they therefore require small inter-site distances to at least one dual-frequency receiver due to the ionospheric influence. Clear guidelines and support for local networks at design and inception stage is required. The datasets should be integrated into the national archive.

- General guidelines for GNSS stations are missing in Switzerland (monumentation, communication, permanent archival). Best practice and standards for networks with scientific purposes and high-quality stations have to be specified or adopted from other standards (RING, UNAVCO, IGS).

- A national data archive for GNSS data and products, which would facilitate cross-application utilization and exchange, and would allow efficient and coherent data curation, does not exist in Switzerland.

6 A step forward: Enhancement of Existing Applications and Future Developments

Based on the described global situation and efforts toward multi-purpose networks combining diverse measurement techniques and communities, improvements of the current status and new future directions for Switzerland are discussed in this section.

6.1 Earthquake Source Characterization and Early Warning

Earthquakes are one of the major hazards to human life and infrastructure. In Switzerland, events with a magnitude of 6 are expected every 50 - 150 years (SED, 2016) and have been identified as the natural hazard with the highest risk potential for Switzerland. The SED is the responsible Swiss federal institution monitoring the seismic activity with high temporal and spatial resolution. The two main components of the national seismic network are the backbone SDSNet (Swiss Digital Seismic Network, which comprises ~40 very sensitive broadband sensors alongside strong motion sensors) and the SSMNet (Swiss National Strong Motion Network, where ~100 strong motion sensors are located typically in towns and cities with elevated earthquake risk), see Fig. 7. The network is particularly dense in the region of Basle and in the Canton of Valais, the regions with highest seismic hazard in Switzerland. In general, the sensitive SDSNet stations are at locations with excellent ground coupling, very low ambient noise, and low temperature and pressure variations. These requirements are typically met at e.g. decommissioned military bunkers and caverns. All seismic stations have continuous, low-latency real-time communication via a few different internet providers to prevent single point failure. The waveform data is distributed to redundant processing hubs at ETH Zürich where it is automatically analyzed and events are detected and characterized within a few 10s of seconds.

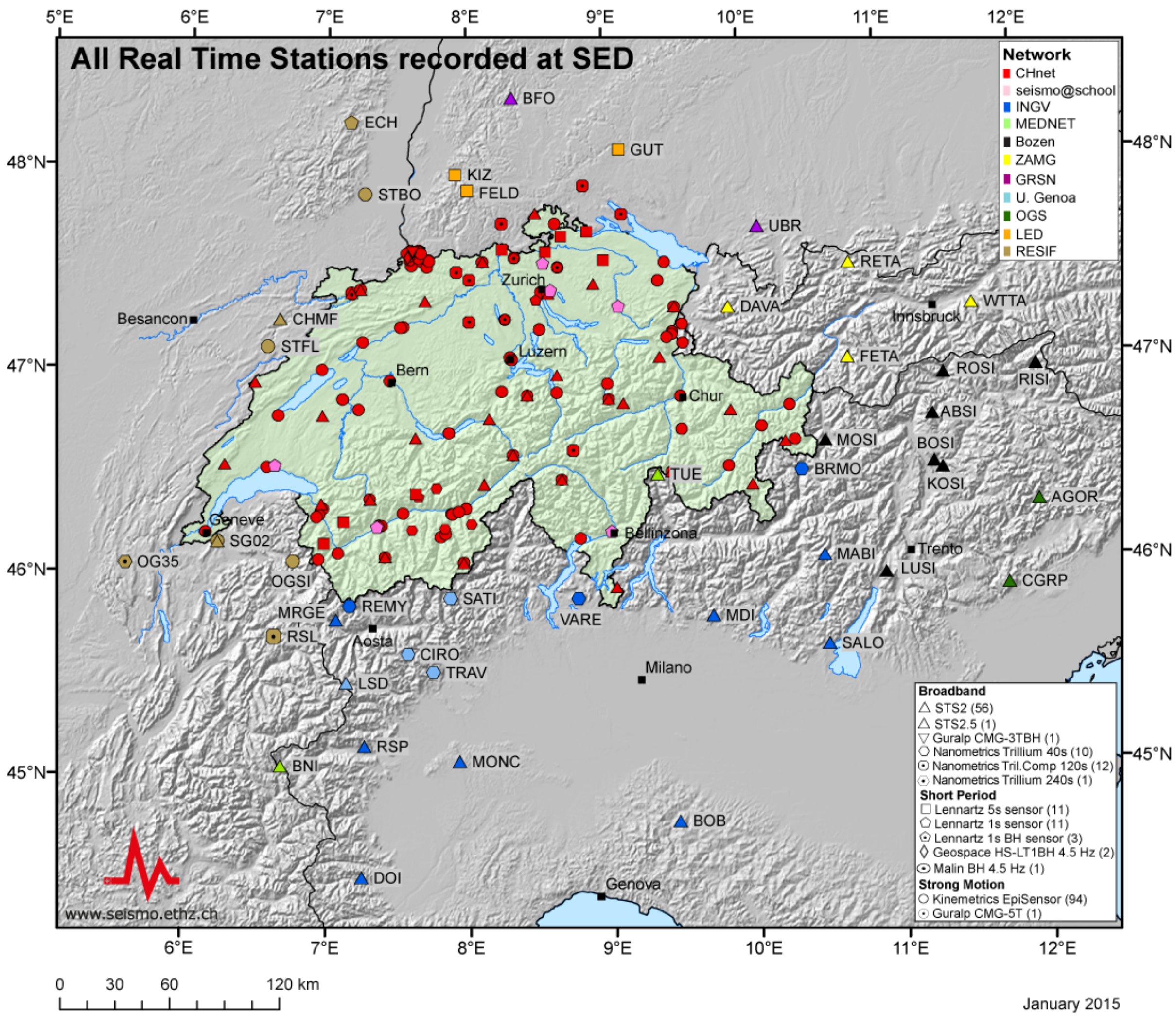

Figure 7: Real-time stations of SDSNet and SSMNet recorded at SED.

Earthquake early warning (EEW) is the attempt to characterize an earthquake within seconds of its occurrence and provide a warning to recipients before strong shaking begins. It is technically achieved by using snippets of data (on the order of 0.5-3s following the initial P-wave energy) from a limited numbers of stations (starting between 2 and 6). EEW works because the initial P-waves propagate faster than the damaging S-waves, and is best designed using a dense seismic network in the source region of earthquakes. It is most useful for larger earthquakes where the area that experiences strong shaking is larger. A major challenge with EEW is that the majority of algorithms to estimate the magnitude assume a point source and a simple source mechanism. For larger earthquakes, with M>6, this assumption is no longer valid. GNSS data that is available on-scale, and with minimal latency, can contribute to EEW algorithms by confirming the occurrence of a large event, constraining the magnitude, and / or estimating the source extent. Even if GNSS datasets are not available in time to provide prior warning to populations and infrastructures, they can be integrated into the general alerting procedures of seismic network operators to verify the magnitudes and source parameters in the case of large, damaging earthquakes. The SED is operating a prototype EEW system since

2009, though there are currently no end users. The system continues to be extended, and future versions should integrate GNSS.

Although GNSS displacement records cannot be expected to exceed the noise until significant earthquakes occur, the Swiss seismic network would strongly benefit from the rapid access to high-rate GNSS measurements as already established in other countries (see Secs. 4.2.4 and 4.2.5), since GNSS sensors have crucial advantages during the rare significant events. Even for moderate earthquakes (M4+) broadband sensors can be expected to saturate in the near-field, within 20km epicentral distance. While strong motion sensors should not saturate even in the strongest earthquakes, GNSS sensors still provide advantages as they 1) do not saturate at even exceptional accelerations (current seismic sensors saturate at 2 g for strong motion, 1 cm/s for broadband), 2) are not sensitive to ground tilting, 3) directly measure displacement without integration. It has been demonstrated in many cases that during strong ground motion as recorded in large earthquakes, there is often good consistency of the accelerations, velocities and displacements estimated from co-located GNSS and seismic data. This additionally indicates that GNSS networks can be used to supplement the current seismic networks and can thus contribute to early-warning systems (Psimoulis et al., 2014, 2015). The former SNF project "High-rate GNSS for seismology" with focus on Switzerland dealt with the recent developments of GNSS receivers with high sampling rates up to 100 sps. Shake table results indicate that high-rate GNSS displacement records that may provide on-scale records from M6 events in the near field should be treated with caution, as signal fidelity in terms of amplitude and phase degrades progressively above 1 Hz (Häberling et al., 2015), though this can be addressed by understanding the true sensor response, which is normally ignored. Sampling beyond 20 sps is not required, as even the highest accelerations expected for Switzerland will not create displacements larger than the current GNSS noise level beyond 10 Hz. Fig. 8 demonstrates the attenuation of high-frequency energy with increased epicentral distance and indicates the highest frequencies, where signals can be expected to be recorded by GNSS (even in post-processing mode) from large earthquakes at different distances. For a target magnitude of M6.5, comparable to the largest known earthquake in Switzerland, GNSS sites would need to be within 20km of the epicenter in order to record energy above 1Hz. This is in good agreement with the analysis based on real data shown in Fig. 9 and with shake table tests generating an M5 earthquake and measured with 100 sps GPS (Häberling, 2015). It is good news for GNSS processing and network design that the magnitude of the GNSS LC (ionosphere-free linear combination) noise between 0.01 and 1 Hz is independent of the baseline length (e.g. 10 m or 100 km) (Häberling, 2015).

Rapid access to high-rate GNSS data can be used to constrain EEW magnitudes during events, where finite rupture is important, and provide important observations that significant dynamic and static displacements are occurring. In addition to EEW processing, high-rate GNSS data can be used in source inversions and ShakeMaps, which can be useful for both near real-time analysis as well as careful post-processing (Fig. 10).

In order to effectively integrate GNSS data with seismic data processing, a number of steps are critical: 1) co-location of the GNSS and seismic sensors should be prioritized at key stations with acceptable inter-sensor distances of up to a few tens of meters to accommodate different sensor demands on location and environment; 2) low-latency / real-time 20 sps GNSS coordinate time series should be made available to SED in standard exchange formats; and 3) combined processing routines, especially above 1 Hz, need to be established. The final combination of both measurement techniques would strongly improve the fidelity of seismograms, from very long periods (static displacement) up to 100 Hz, and would also benefit other earthquake products such as ShakeMaps (Cauzzi et al., 2015).

Requirements for the GNSS network:

- high spatial density required, inter-site distance shorter than 10-20 km due to limited spatial extent of large displacements induced by M5-6 earthquakes;
- co-location with seismic instruments within some tens of meters (for key stations);
- optimum properties of the basement and monumentation, solid rock;
- sampling rate between 10-20 sps;
- online capability with a bandwidth of at least 30 kbps (for RTCM3 1004 message);
- minimum data latency of correction streams (< 10 s);
- real-time PPP processing for early warning (EEW);
- near real-time displacements from GNSS processing (swipos-INFRA and swipos-PP).

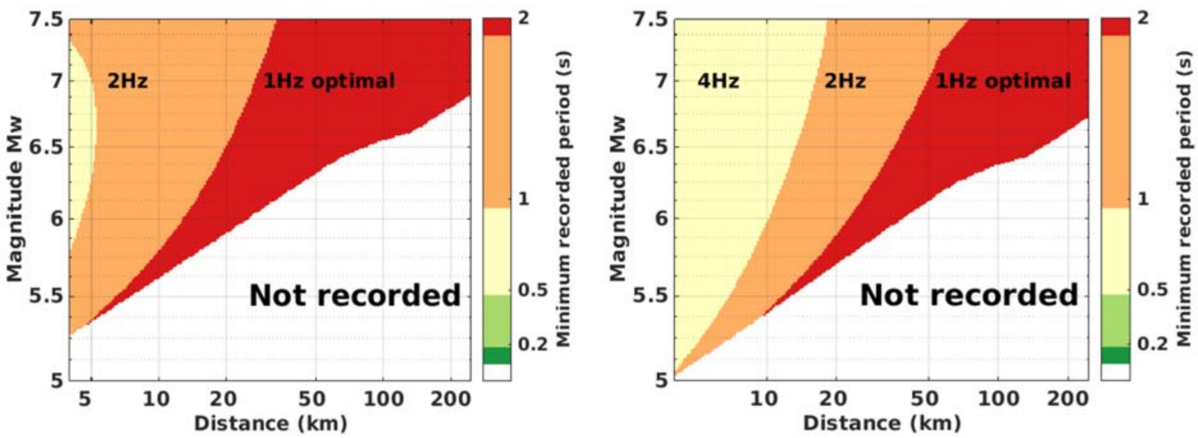

Figure 8: Recording capability of GPS (left) in real-time mode (PPP processing, mean noise level) and (right) in post-processing mode (average GAMIT noise level) for Switzerland (Michel et al., 2016)

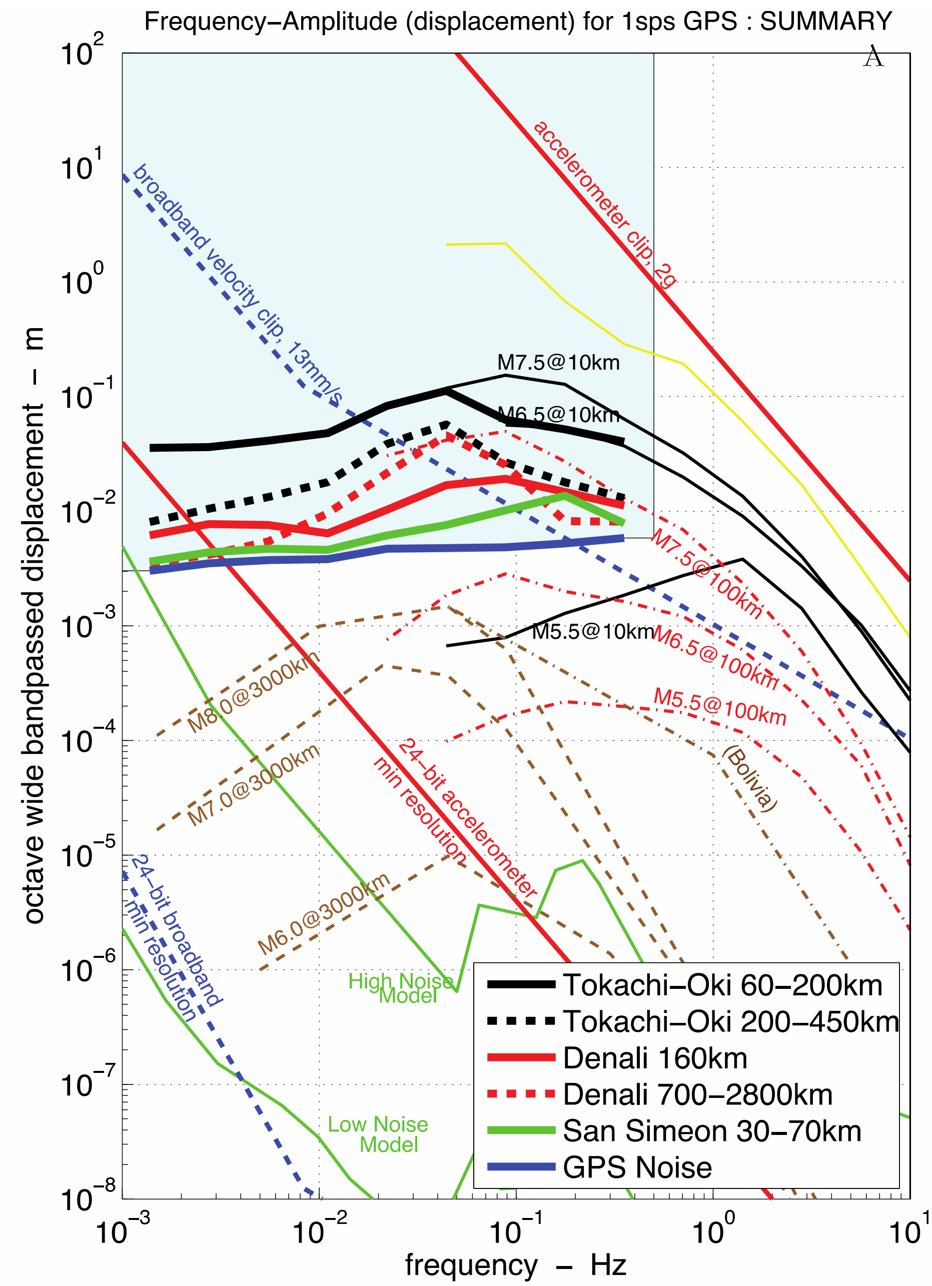

Figure 9: Comparison of the average amplitude / frequency for near source (~10km) and regional (~100km) earthquakes, the limits of standard seismic sensors (strong motion accelerometer, broadband), and the observed amplitudes for high-rate GPS signals from noise as well as in large earthquakes. The light blue box indicates the amplitude - frequency range that can be covered by high-rate 1sps GNSS streams. (Clinton et al., 2007)

6.2 Earthquake Task Force / Aftershock Campaigns

In the case of a significant seismic event, co- and post-seismic displacements can be expected in the vicinity of the epicentral region. It is then critical to re-visit sites from the LV95 network close to the epicenter that may experience measurable displacements as soon as possible. A 'Task Force' is required to temporarily occupy a number of critical sites rapidly after an event (within hours, or at most 1-2 days) and perform continuous high-rate monitoring until the aftershock sequence subsides and post-seismic displacements return to ambient noise levels.

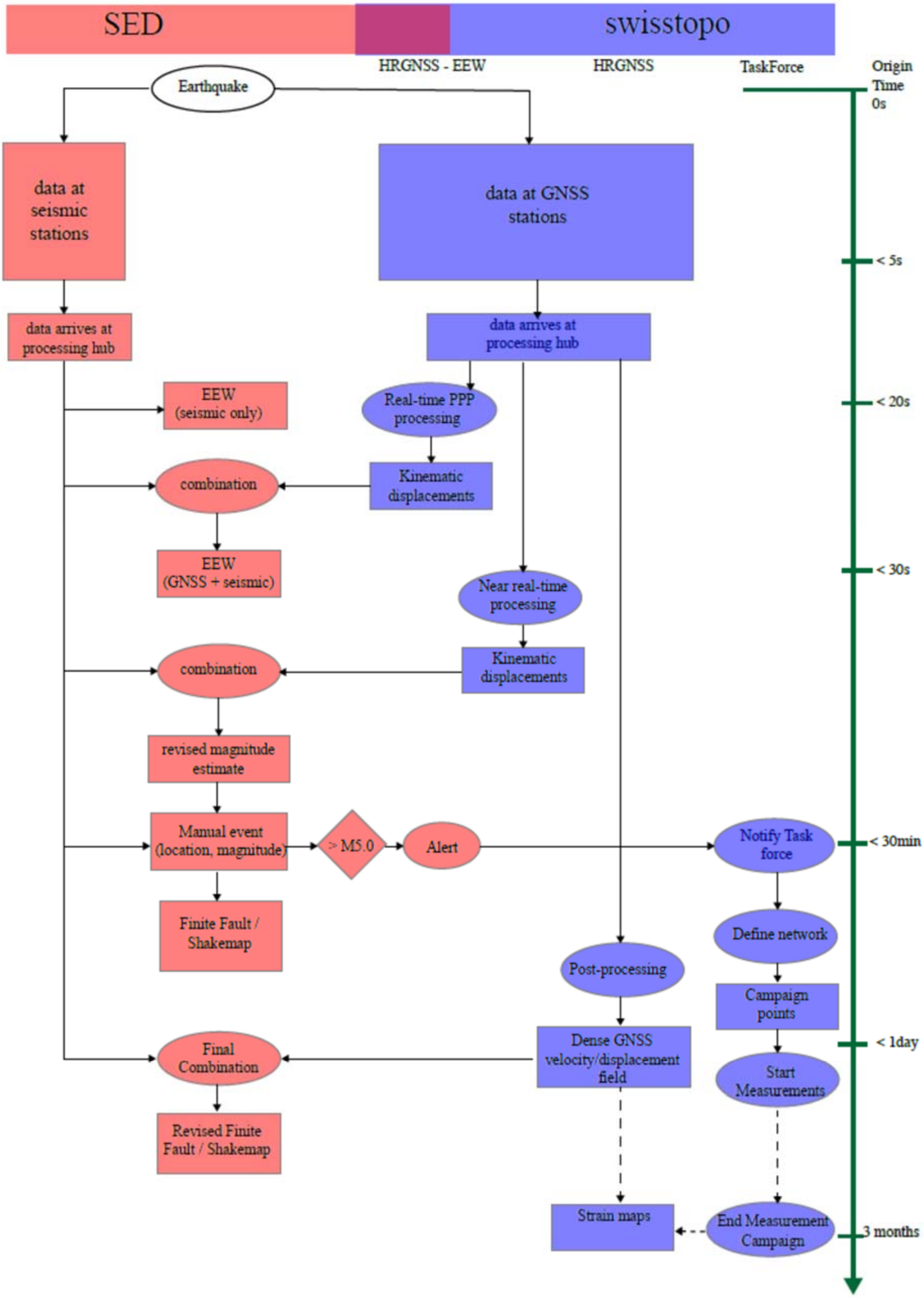

Figure 10: Overview of future integrated processing capabilities for seismic and geodetic measurements during large earthquakes in Switzerland.

A next generation plan for geo-monitoring should establish this Task Force and enable its effective management and deployment. A procedure of actions of this Task Force should be implemented according to Fig. 10. The collected GNSS displacement data should be integrated into the national seismic archive and included in post-processing products.

In a first stage the Task Force station equipment may only provide on-site data collection (no real-time communication). The long-term target should be to have the temporary stations in the Task Force operating with real-time communications, so data can be processed in near real-time, and eventually included in a seismic monitoring infrastructure that includes GNSS data in event characterization.

Requirements for the Task Force:

- establishment of a set of temporary GNSS stations dedicated to the Task Force;
- establishment of responsibilities and rules for Task Force deployments;
- establishment of procedures to archive and process the data, real-time communications to be considered.

6.3 Geodynamics

The estimation of a precise kinematic model of tectonic motion (e.g. the Swiss kinematic model CHKM) helps to better understand the tectonic processes and is a key ingredient in seismic hazard assessment. The knowledge and monitoring of tectonic processes is additionally essential for critical infrastructures and major projects such as the disposal of radioactive waste. Previous studies (see Sec. 5.1) showed the feasibility of strain field determination based on geodetic techniques. The current coverage of GNSS permanent stations is, however, insufficient to constrain the velocity and strain rate field necessary for a detailed interpretation at a local scale. More than 200 points were necessary to extract the kinematic velocity field for a regional scale due to the problematic separation of local effects and tectonic movements. Additionally, the extremely small deformations in Switzerland require measurement periods of decades for a reliable quantification. For the height component, GNSS has to be supported by leveling data. Periodically measured campaign points run the risk of including additional measurement uncertainties due to different operators and equipment (e.g. antennas) and specific circumstances (e.g. meteorology, troposphere) shortly before and during the measurement campaign. Therefore, it is preferable to have a single operator that follows consistent measurement and processing procedures for campaigns over decades (as for the past CHTRF campaigns).

The equipment of permanent GNSS stations as well as for measuring the LV95 network have to be at least dual-frequency receivers with high-quality antennas. The sampling rate is not critical for this application. Processing strategies (e.g. with the Bernese GNSS software) are well established and already used for the permanent monitoring of the current networks by swisstopo. The stations do not need a real-time capability of data streaming. However, the monumentation and its monitoring are essential in case of long-term aspects. Improvement of the monumentation is required in order to improve the displacement accuracy and to provide long-term stability. Additional monitoring of the monumentation (e.g. using accelerometers and tiltmeters mounted below the pole) might be beneficial, together with a (multi-year) re-measurement of all AGNES local monument positions, to detect not only monument changes but also local disturbances like sliding of the subsurface.

Requirements for geodynamics:

- spatial densification;
- high-quality receivers and antennas;
- periodic GNSS and levelling campaigns;
- long-term measurements and long-term stability of the monumentation;
- monitoring of the monumentation and local effects, possible relocation of some sites;
- sampling rate 30 sec;
- no real-time access needed;
- standardized post-processing and data management;
- standardized observation strategy for campaigns

6.4 Local Monitoring

As described in Sec. 5.3, there is an increasing number of small local networks for the monitoring of critical infrastructure or natural hazards. Two different network concepts can roughly be distinguished, 1) monitoring of a local area with low-cost receivers (only single frequency receivers with short baselines of few kilometers, often temporary only) that require a nearby permanent dual-frequency station (due to the ionosphere) for a correct connection to the national geodetic reference frame (AGNES) or 2) a small local permanent GNSS network with high-quality equipment and well mounted sites. The central data storage of well mounted permanent sites and the inclusion into the automated processing of swisstopo would be in line with the concept of a common and unique reference frame for all deformation monitoring applications. However, best practice and site guidelines have to be specified, if only high-quality data should be integrated in the swisstopo data center. The local low-cost networks would also profit from a denser GNSS reference network especially in Alpine regions.

Special applications of local GNSS monitoring networks are the ground-based augmentation systems (GBAS) for aviation. GBAS improves the integrity during GNSS-based approaches while monitoring ionosphere and troposphere in real-time in critical regions.

Local monitoring networks could also be operated as a Public Private Partnership, where national/cantonal institutions define the requirements and private surveyors are responsible for the maintenance, data collection, and processing.

Requirements for local monitoring networks:

- densification of permanent sites in regions of interests;
- sampling rate of at least 1 sps (20 sps ring buffer) with real-time access;
- data dissemination and inclusion into the automated post-processing;
- strong (precise and reliable) connection to the national geodetic reference frame;
- definition of best practices for networks, including guidelines for hardware, monuments and data management.

6.5 Meteorology

Reliable and accurate short-range quantitative weather forecasting requires precise information of the initial state of the atmosphere. GNSS offers the possibility to determine the humidity in the troposphere. As already described in Sec. 5.2, the GNSS signal delays are used to estimate the integrated water vapor along the path from the GNSS satellite to the receiver, which is finally mapped to the zenith direction as an artificial ZTD. Diverse projects (see Sec. 5.2) have already demonstrated that the water vapor content derived from GNSS measurements accurately matches that retrieved from radiosondes. Currently the area of Switzerland is covered by only one radiosonde station in Payerne (VD). Therefore, the numerical weather models of MeteoSwiss would benefit from an assimilation of densely distributed GNSS measurements, especially if at least the major stations of the Swiss meteorological network SwissMetNet with currently a total of about 300 stations would additionally be equipped with GNSS receivers. In addition to a spatial densification, an improved temporal resolution enables a more reliable hydrological hazard assessment, e.g. for extreme flooding events. Even already established positioning services (swipos) can be improved by a better tropospheric parameter estimation, making it useable for low-cost RTK receiver applications.

In addition to the installation of an increased number of GNSS stations, the data exchange is crucial. The current AGNES and SwissMetNet stations offer a very good infrastructure including internet access. All GNSS data has to be collected and processed by swisstopo. Up to now only ZTDs are distributed (e.g. to E-GVAP). An even better assimilation can be reached when directly integrating the slant delays into the weather models.

Requirements for GNSS meteorology:

- At least major SwissMetNet stations (e.g. 120 out of approx. 300) should be equipped with dual-frequency GNSS receivers;
- GNSS network densification, especially in Alpine regions, with additional stations at different elevations;
- sampling rate 1 - 30 s;
- ZTD products every hour, slant delays every 30 s
- definition of an internationally agreed file format for GNSS slant delays

6.6 National Survey and Positioning Services

A selective densification of the AGNES network for the need of national surveying and for positioning services is appropriate. Such a densification would improve the distribution of the AGNES stations (especially in elevation), which would enhance the quality of tropospheric modeling especially for positioning services. Since during national measurement campaigns (such as CHRTF2016) AGNES serves as "backbone", shorter distances to the next reference station and a higher redundancy in the network will further improve the results of these campaigns, and potentially the determination of the Swiss kinematic model CHKM (see Sec. 6.3).

Kinematic applications of the positioning services (e.g. machine control, drones, UAV, precise car navigation, etc.), especially low-cost RTK applications in city regions, are increasing and may, in the near future, require the use of high-rate data (> 1 sps). This corresponds to the demands of seismological applications. Higher data sampling rates at the stations need to be combined with improved communication links between the stations and the control center in order to support larger data rates, with minimal data latency.

Requirements for national survey and positioning services:

- selective spatial densification of AGNES;
- higher data rate for communication links, real-time capability.

6.7 Summary

A selective spatial densification of GNSS stations across Switzerland is evidently called for, especially in seismogenic and Alpine regions, based on the clear benefit this would bring to both, existing and future applications and products. Further key developments for the future GNSS monitoring infrastructure are the co-location of different sensors in order to use synergies and to improve the reliability and redundancy, and the long-term stability considering the sensor monumentation and network operation. There will be an obvious move towards real-time processing of data with high sampling rates. This will require changes at the stations: high-quality antennas and receivers that support high sampling and more reliable communication links. All local monitoring networks must have a precise and reliable connection to the national geodetic reference frame. A combined processing, a central (or at least coordinated) data management and open data exchange are additionally crucial to improve on the current situation and to keep pace with international developments. Finally, these aspects and requirements should be defined in “best practices” for use not only by swisstopo but also by partner programs interested in operating GNSS networks within Switzerland. These would include guidelines for hardware, monuments, communications and data management.

The following Table 4 gives an overview of the applications and a summary of the requirements.

Applications	**Requirements**
Seismology	High spatial density of the multi-GNSS network and co-location with seismic instruments, inter-station distance of 10-20 km, 1 sps (ring buffer 20 sps for 14 days), real-time access, real-time PPP processing and more accurate near real-time processing (2 min)
Task force	High point density of campaign points, available equipment, well-defined procedures of task force measurements (over 3 months), high sampling rate up to 20 sps, no real-time access, post-processing
Geodynamics	Densification, long-term measurements and stability of the monumentation, post-processing
Local monitoring	Densification (ionosphere), reference stations linked to AGNES, real-time access, reference station with real-time processing possibility
Meteorology	Densification especially in Alpine regions and at different heights, real-time access, near real-time processing
National Survey	Selective densification (to improve positioning services), monument monitoring, real-time capabilities, post-processing

	Spatial densification	Co-location	High-rate data	Real-time processing	Central data management
Seismology	x	x	x	x	x
Task force	x	(x)	x		x
Geodynamics	x				x
Local monitoring	x	(x)	(x)	(x)	x
Meteorology	x	x	(x)	(x)	x
National Survey	x		(x)	(x)	x

Table 4: Top: Summary of the requirements for new and enhanced existing applications using permanent GNSS networks in Switzerland. Bottom: Matrix showing the importance of some requirements for different applications. The brackets denote a requirement of not highest priority for the corresponding application.

7 Recommendations for the National GNSS-Geomonitoring Infrastructure in Switzerland

There is a growing demand for operating a multi-purpose GNSS network in Switzerland that complements other monitoring infrastructures and enables excellent, next generation science and services. Building such a network poses various challenges and requires some clear strategic actions. First and foremost, a single and strong agency should be responsible for 1) coordinating the GNSS monitoring infrastructures, 2) operating a data management and routine analysis center, and 3) proposing standards and guidelines. swisstopo is best placed to be this agency.

The GNSS monitoring network that focuses on providing nationally important geodetic services and scientific applications should continue to be operated by a federal institution that is able to guarantee quality and long-term operation. Affiliated networks with a purpose outside of the core business can be operated by private companies or other institutions, though, where appropriate, these networks should follow standards set by the federal agency and should provide data for routine processing, permanent archival, and open dissemination.

For a multi-purpose GNSS network in Switzerland, swisstopo is today the responsible institution and should likely remain so for the next decades. To properly address the future challenges of GNSS geomonitoring, a densification of the swisstopo AGNES network with high-quality GNSS stations is necessary for both service and science.

A key development for Swiss geomonitoring is the establishment of an extended data center that includes a new data portal for 1) permanent and persistent archival and data management of all high-quality GNSS data; 2) open access to products and raw data and 3) provision of real-time data products of relevance to appropriate authorities, e.g. to the SED for earthquake monitoring (including EEW).

The required densification of the current network and data exchange with seismic and meteorological networks will greatly improve the seismic and hydrological hazard assessment and in the case of earthquakes, can potentially be used in routine event analysis including early warning.

The key recommendations are summarized in the following actions:

1. **Spatial densification** of the backbone AGNES network with new stations of geo-dynamic quality. The targets are
   i) general densification to a spacing of 10-20 km;
   ii) improved height resolution in key mountainous areas;
   iii) selective densifications in regions with elevated seismic risk.

2. **Co-locate** key stations in AGNES with seismic stations and meteorological sensors. At minimum, SED, swisstopo, and MeteoSwiss shall consult each other when **planning future new monitoring stations.**
3. **Improve infrastructure** at all AGNES and affiliated network stations to enable a sampling rate of 20 sps. Communications shall be upgraded and hardened to provide sufficient bandwidth and operated with minimum latency. swisstopo shall establish a processing chain with focus on real-time high-rate GNSS data with minimal data latency.
4. swisstopo and SED shall establish a **clear framework for integrating high-rate GNSS in seismic network procedures**, including integration of event displacements in the SED waveform archives with minimum data latency.
5. swisstopo shall define **standards and guidelines** to be applied by all agencies that may develop either high-quality permanent GNSS stations or lower quality temporary deployments that need to integrate with AGNES. Emerging community standards shall be followed where possible. swisstopo shall lead the GNSS community coordination at the national and international level, e.g. with EPOS.
6. swisstopo shall continue to be responsible for the **establishment of a national data center** for central GNSS processing and analysis, including real-time products, and the permanent archival of high-quality GNSS data of the new expanded automated GNSS network.
7. **Exchange formats and dissemination tools** between swisstopo and the end user communities shall be defined and an open data policy for scientific purposes shall be pursued.
8. An operational **task force** shall be established for rapid response after a significant seismic event – equipment and resources shall be allocated, with clear responsibilities assigned.
9. The periodic **measurement campaigns** for the swisstopo LV95 network shall be continued with a maximum re-measuring period of six years.

The obvious and necessary next step towards building future Swiss GNSS geomonitoring infrastructure is a financial feasibility study regarding the implementation of the identified recommendations, and considerations about the need for and potential sources of additional financing.

Contributing Authors (alphabetically ordered)

Clinton, John	Swiss Seismological Service, ETH Zürich
Geiger, Alain	Institute of Geodesy and Photogrammetry, ETH Zürich
Häberling, Simon	Institute of Geodesy and Photogrammetry, ETH Zürich
Haslinger, Florian	Swiss Seismological Service, ETH Zürich
Rothacher, Markus	Institute of Geodesy and Photogrammetry, ETH Zürich
Wiget, Adrian	Swiss Federal Office of Topography swisstopo
Wild, Urs	Swiss Federal Office of Topography swisstopo

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Appendix A – Abbreviations

AGNES	Automated GNSS network for Switzerland (operated by swisstopo)
APOS	Austrian Positioning Network and Services
BAFU	Swiss Federal Office for the Environment (FOEN)
BEV	Bundesamt für Eich- und Vermessungswesen, Vienna (A)
BKG	German Federal Institute of Cartography and Geodesy, Frankfurt (D)
BSM	Borehole Strainmeters
CHKM	Swiss Kinematic Model
CHTRS	Swiss Terrestrial Reference System
CHTRF	Swiss Terrestrial Reference Frame(s)
ECMWF	European Centre for Medium-Range Weather Forecasts
EEW	Earthquake Early Warning
EPN	European Permanent Network (EUREF)
EPOS	European Plate Observing System
EUREF	IAG Reference Frame Sub-Commission for Europe
ETRS	European Terrestrial Reference System
ETRF	European Terrestrial Reference Frame(s)
FOEN	Swiss Federal Office for the Environment
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GREF	Integriertes Geodätisches Referenznetz
HRGNSS	High-Rate GNSS
IAG	International Association of Geodesy
IGP	Institute of Geodesy and Photogrammetry, ETH Zurich
IGS	International GNSS service
ItalPoS	Italian Positioning Network and Services
ITRS	International Terrestrial Reference System
JPL	Jet Propulsion Laboratory
LSM	Long-Baseline Surface Laser
LV95	National Survey LV95 (Swiss reference frame and network of passive points)
NaGNet	GNSS monitoring network of NAGRA
NAGRA	National Cooperative for the Disposal of Radioactive Waste
PBO	Plate Boundary Observatory

PNAC	Permanent Network Analysis Center (swisstopo)
PPP	Precise Point Positioning
PWV	Precipitable Water Vapor
RefNet	Private GNSS Reference Network in Switzerland
RING	Rete Integrata Nazionale GPS
RTCM	Standards of the Radio Technical Commission for Maritime Services
RTK	Real-time Kinematic
SAPOS	German Real-time Positioning Service
SCIGN	Southern California Integrated GPS Network
SDSNet	Swiss Digital Seismic Network
SED	Swiss Seismological Services
SGK	Swiss Geodetic Commission (Schweizerische Geodätische Kommission)
SGPK	Swiss Geophysical Commission (Schweizerische Geophysikalische Kommission)
SSMNet	Swiss National Strong Motion Network
swipos-GIS/GEO	Real-time kinematic swipos service (swisstopo)
swipos-INFRA	Real-time raw data swipos service (swisstopo)
swipos-NAV	Real-time differential-code swipos service (swisstopo)
swipos-PP	Post-processing swipos service (swisstopo)
swisstopo	Swiss Federal Office of Topography
TERIA	French Positioning Network and Services
TLS	Terrestrial Laser Scanning
UNAVCO	US-based non-profit university-governed consortium (formerly *University NAVSTAR Consortium*)
USGS	US Geological Survey
VRS	Virtual Reference Station
ZTD	Zenith Total Delay

Appendix B – Tables

Table B-1 AGNES stations (Jan. 2017)

Station	*Class*	*E [m]*	*N [m]*	*H [m]*	*Start*	*sampling [s]*	*Operator*	*Receiver*	*Antenna*	*System/Frequency*	*Online*	*static/moving*
AIGE	C	2498943	1122661	421	2009	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
ARDE	A	2811209	1184302	1499	2001	30 / 1	swisstopo	Trimble NetR9	TRM33429.20+GP	GPS L1/L2/L5	yes	static
ARD2	A	2811214	1184301	1499	2007	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
BOUR	A	2584293	1249277	891	2001	30 / 1	swisstopo	Trimble NetR9	TRM33429.20+GP	GPSL1/L2/L5	yes	static
BOU2	A	2584282	1249269	893	2008	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
DAVO	A	2783516	1187452	1598	1998	30 / 1	swisstopo	Trimble NetR9	TRM29659.00	GPS L1/L2/L5	yes	static
DAV2	A	2783527	1187464	1597	2007	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
EPFL	C	2533187	1152613	407	1998	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
ETHZ	C	2680904	1251246	547	1998	30 / 1	swisstopo	Trimble NetR9	TRM29659.00	GPS L1/L2/L5	yes	static
ETH2	C	2680910	1251259	547	2007	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
FALE	C	2736752	1185264	1295	2001	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
FHBB	C	2615058	1264811	329	1998	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
FRIC	A	2650703	1264293	678	2001	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
FRI3	A	2650681	1264293	679	2011	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
HABG	B	2656862	1177632	1098	2006	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
HOHT	C	2624959	1129829	934	2000	30 / 1	swisstopo	Trimble NetR9	TRM33429.20+GP	GPS L1/L2/L5	yes	static
HOH2	C	2624963	1129829	934	2007	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
HUTT	C	2630058	1221197	730	2001	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
JUJ2	C	2641800	1155200	3450	2016	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
KALT	C	2718899	1230858	429	2008	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
KREU	C	2729349	1278156	483	2001	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
LOMO	C	2704160	1114349	387	1998	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
LUZE	B	2665476	1213379	493	2001	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
MAR2	A	2571556	1107917	592	2008	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
MAR3	A	2571556	1107925	593	2015	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
NEUC	C	2562108	1204872	454	1998	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
OALP	B	2694527	1168390	2090	2014	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
PAYE	C	2562243	1184673	498	2000	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
SAAN	A	2589459	1151594	1368	2001	30 / 1	swisstopo	Trimble NetR9	TRM33429.20+GP	GPS L1/L2/L5	yes	static
SAA2	A	2589460	1151589	1368	2009	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
SAM2	C	2787248	1155678	1713	2016	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
SANB	A	2734103	1147324	1653	2001	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
SAR2	B	2757374	1205587	1218	2011	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
SCHA	C	2691301	1288150	591	2001	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
STAB	C	2716742	1079364	366	2001	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
STA2	C	2716747	1079361	366	2007	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
STCX	C	2528465	1186121	1104	2001	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
STGA	C	2743855	1256300	707	2000	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
ZERM	A	2622726	1094473	1879	2005	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static
ZIMM	B	2602030	1191775	906	1993	30 / 1	swisstopo	Trimble NetR9	TRM29659.00	GPS L1/L2/L5	yes	static
ZIM2	B	2602011	1191774	906	2007	30 / 1	swisstopo	Trimble NetR9	TRM59800.00	GNSS L1/L2/L5	yes	static

Table B-2 COGEAR stations in the canton of Valais (Jan. 2017)

Station	E [m]	N [m]	H [m]	Start	sampling [s]	Operator	Receiver	Antenna	System/Frequency	Online	static/moving
CRDM	2607002	1119785	2333	2006 03 01	30 / 0.1	GGL	Trimble NetRS	Trimble	GPS L1/L2	yes	static
ERDE	2588525	1120393	730	2005 10 06	30 / 1	GGL	Trimble NetR9	Trimble	GPS L1/L2	yes	static
FIES	2651842	1142742	2360	2011 11 11	30 / 0.04	GGL	Leica GRX1200	Leica	GNSS L1/L2	yes	moving
HOGR	2618012	1092200	3463	2011 02 03	30 / 0.04	GGL	Leica GRX1201	Leica	GNSS L1/L2	yes	moving
KREB	2640619	1109785	2412	2014 10 29	30 / 0.04	GGL	Leica GRX1202	Leica	GNSS L1/L2	yes	static
RAND	2625632	1107181	2415	2011 05 26	30 / 0.04	GGL	Leica GRX1203	Leica	GNSS L1/L2	yes	static
SANE	2589054	1134435	2025	2005 10 07	30 / 0.1	GGL	Trimble NetRS	Trimble	GPS L1/L2	yes	static
SIMP	2644802	1121066	1962	2011 06 25	30 / 0.04	GGL	Leica GRX1200	Leica	GNSS L1/L2	yes	static
VARE	2612626	1129280	652	2005 10 07	30 / 1	GGL	Trimble NetR9	Trimble	GPS L1/L2	yes	static
WEHO	2602630	1136743	2915	2006 09 06	30 / 0.1	GGL	Trimble NetRS	Trimble	GPS L1/L2	yes	static