Applications scientifiques du transfert de temps optique spatial

Scientific applications of spatial optical time transfer

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Résumé du projet en Français :
Le système de transfert de temps par lien laser T2L2 a été lancé par le CNES sur Jason2 en 2008.
La technique est basée sur la télémétrie laser, dont les performances en termes de précision et d'exactitude sont respectivement de 10 ps et inférieures à 50 ps. Le traitement des liens optiques obtenus à partir du réseau international des stations laser (en appui de l'orbitographie des satellites) a permis de constituer à l'OCA une base de données très importante. Ceci constitue le premier réseau d'horloges au sol dont des maser-Hydrogène, reliées entre elles par des liens spatiaux. Plusieurs campagnes de transfert de temps par laser ont été effectuées afin d'établir les performances du transfert de temps par laser ; la stabilité de chaque lien sol-satellite a été estimée à 6 ps @ 60 secondes, l'exactitude s'établit à 120 ps. En outre, une interopérabilité des systèmes de transfert de temps GNSS et laser a été développée, permettant de mieux appréhender les différences et comportements (bruits) entre les techniques. À terme, nous envisageons avec le groupe allemand (Université Technique de Munich (UTM) et station laser de Wettzell), de porter l'interopérabilité aux données ELT.
Ce projet porte sur les applications scientifiques de T2L2 et s'appuie, d'une part sur les résultats probants des analyses, les données disponibles, les campagnes à venir et les comparaisons laser-GPS, et d'autre part sur les perspectives futures en physique et en géodésie notamment avec le système ELT (basé sur le laser) en lien avec le système spatial ACES/Pharao.

Abstract in English:
The Time Transfer by Laser Link (T2L2) experiment was launched in June 2008 aboard Jason-2 at 1335 km altitude. The principle is based on the laser ranging technology involving a ground h-maser and ps resolution and precision event timers on the ground, and a dedicated optics and electronic device on-board. The resulting time stability of T2L2 in such conditions is of 6 ps @ 60 seconds with an accuracy of around 120 ps. The on-board timer is using the DORIS oscillator which is the reference clock for this important tracking Doppler system of CNES and IGN which currently is aboard multi-satellite missions.
The proposed activities lie in the field of time & frequency for both space and ground applications. T2L2 is expected to read the DORIS space oscillator to a precision level never reached before; this has to be studied from the design of each instrument and from the great amount of data acquired by the T2L2 mission. T2L2 is similar to the laser time transfer instrument, ELT (Germany) developed for ACES/Pharao, thus a synergy is going to be developed between both missions. The other activity is dedicated to the possibility of computing ground-to-ground time transfer links between laser stations of the international network. Obviously, comparisons of the computed optical links with GNSS ones have to be planed in terms of campaigns, methods and data analysis.

Résultats marquants :
Deux types de résultats marquants ont été présentés en colloques et publiés (Rg-A à lecteurs). Le transfert de temps optique laser T2L2 est à même de lire les déviations de fréquence de l'oscillateur bord de la mission Jason-2 en fonction du temps, à plusieurs 10^{-13} en dF/F0 ; nous avons tout de suite identifié les causes, radiatives, de ces déviations et avons proposé un modèle à la communauté. Celui-ci publié fin 2015, a eu beaucoup de succès puisqu'il s'agit de l'oscillateur DORIS (CNES et IGN). Le second résultat est lié au transfert de temps sol-sol par laser sur T2L2 & par GPS. Les résultats en Europe (Vue Commune) ont atteint un très grande exactitude, < 0.2 ns après une campagne menée en 2013, et ont été publiés en 2014. En Vue-non-Commune (Europe-Chine), il a d'abord été appliqué sur 1500 secondes, puis > 10,000 secondes par intégration du modèle de fréquence et des déviations relativistes. L'article sur la métrologie de ce transfert de temps sol-sol calibré est soumis fin 2017. Un

autre article, de nature plus applicative en géodésie spatiale, a consisté à calculer l'intégralité de la synchronization (à 3 ns) de toutes les stations laser du réseau international qui a participé à T2L2 pendant plusieurs années. Résultat publié en mars 2017.

Highlights:

The scientific applications of the optical time transfer have been published in two folds. The first application concerned the reading of the oscillator of the Jason-2 mission which is the reference clock of the DORIS (CNES and IGN) Doppler tracking system. A frequency model has been developed showing the deviation of frequency due to radiations, essentially. The model has a great success in the space geodesy community, because some other DORIS oscillators have same problems. The second application concerned the ground-to-ground time transfer via T2L2. In common view over Europe, the results are at the metrological level, < 0.2 ns accuracy (laser vs. GPS), after a campaign carried out in 2013. On the other hand, the non common view time transfer has been computed from our frequency model, between 1500 and more than 10,000 seconds, from data acquired between Europe and China in 2016 on the one hand and from data acquired by the international laser network since the beginning of the T2L2 mission. The results are at 0.5 ns level (accuracy) and 3 ns (repeatability), respectively for both applications in metrology and in space geodesy.

Publications and communications linked with the funded project:

Peer-reviewed articles:

Samain E., G.D. Rovera, J.-M. Torre, C. Courde, A. Belli, P. Exertier, P. Uhrich, Ph. Guillemot, R. Sherwood, D. Xue, H. Xingwei, Z. Zhang, W. Meng, Z. Zhongpin (2017) Time Transfer by Laser Link (T2L2) in non common view between Europe and China, *Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Special Issue, TUFFC-08510-2017 Submitted November 2017.

Exertier P., A. Belli, J.M. Lemoine (2017) Time biases in laser ranging observations: a concerning issue of Space Geodesy, *JASR*, 60, 948-968.

Exertier P., Samain E, Courde, C; Aimar, M; Torre, J-M; Rovera, G D; Abgrall, M; Uhrich, P; Sherwood, R; Herold, G; Schreiber, K; Guillemot, Ph (2016) Sub-ns time transfer consistency: a direct comparison between GPS CV and T2L2, *Metrologia*, 53(6), 1395.

Belli A., Exertier P., Samain E., Courde C., Vernotte F., Jayles Ch., Auriol A. (2015) Temperature, Radiation and Aging Analysis of the DORIS Ultra Stable Oscillator by means of the Time Transfer by Laser Link Experiment on Jason-2, *Advances in Space Research DORIS Special Issue*, 58(12), 2589-2600.

Jayles Ch., Exertier P., N. Martin, J.P. Chauveau, C. Tourain, A. Auriol, Ph. Guillemot (2015) Comparison of the frequency estimation of the DORIS/Jason2 oscillator thanks to the onboard DIODE and Time Tranfer by Laser Link experiment, *Advances in Space Research DORIS Special Issue*, P. Willis (Ed), 58(12), 2601-2616.

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Laas-Bourez M., Courde C., Samain E., Exertier P., Guillemot Ph., Torre J.M., Martin N., Foussard C. (2015) Accuracy validation of T2L2 time transfer in co-location *Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 62(2), 255-265

Exertier P., E. Samain, N. Martin, et al. (2014) Time Transfer by Laser Link : Data analysis and validation to the ps level, *Adv. Space Res.,* 54(11), 2371-2385

Samain E., P. Vrancken, Ph. Guillemot, P. Fridelance, P. Exertier (2014) Time Transfer by Laser Link (T2L2) : Characterization and Calibration of the flight instrument, *Metrologia*, 51, 1-13

Proceedings:

Belli A., Exertier P., Vernotte F. and Jayles Ch. (2017) DORIS-class Oscillator Under Radiations: the Jason Family of Satellites. Proceedings of the 31st European Frequency and Time Forum (EFTF/IFC), Besançon, July 10-13, 2017.

Samain E., G.D. Rovera, J.-M. Torre, C. Courde, P. Exertier, A. Belli, P. Uhrich, R. Sherwood, D. Xue, H. Xingwei, Z. Ziang, W. Meng, Z. Zhongpin (2017) Time Transfer by Laser Link (T2L2) in non Common View between Europe and China. Proceedings of the 31st European Frequency and Time Forum (EFTF/IFC), Besançon, July 10-13, 2017.

Belli A., Exertier P., E. Samain, C. Courde, J-M. Torre, F. Vernotte (2015) Synchronization of distant Laser stations thanks to Time Transfer by Laser Link : Proposal for a dedicated campaign, Proceedings of the Technical Laser Ranging Workshop, Matera, Italy, October 26-30, 2015.

Belli A., Exertier P., Samain, E., Courde, C., Vernotte, F., Auriol, A. and Jayles, Ch. (2015) Characterization of an ultra stable quartz oscillator thanks to Time Transfer by Laser Link (T2L2/Jason2). Proceedings of the 29th European Frequency and Time Forum (EFTF/IFC), Denver, Colorado, US, April 13-17, 2015, doi:10.1109/FCS.2015.7138964, pp 808-812.
Exertier P., C. Courde, N. Martin, J.-M. Torre, J.-L. Oneto, M. Laas-Bourez, Ph. Guillemot, S. Leon (2013) T2L2: Five years in space, Proceedings of the EFTF & International Frequency Control Symposium (EFTF/IFC) 2013, Prague, Rep. Tcheque, July 21-25 2009, DOI: 10.1109/EFTF-IFC.2013.6702281, pp. 632-635.

Oral communications:

Belli A., P. Exertier, F.G. Lemoine, N.P. Zelensky, D.S. Chinn, H. Capdeville, The T2L2 contribution to Precise Orbit Determination and Positiong, Ocean Surface Topography Science Team (OSTST) meeting, Miami, FD, US, October 23-27, 2017
Belli A., P. Exertier, E.C. Pavlis, F. Lemoine, From Time Transfer by Laser Ranging to Space Geodesy Products, International workshop on Laser Ranging Technical workshop, Riga, Latvia, October 2017.
Belli A., Exertier P., Vernotte F. and Jayles Ch., DORIS-class Oscillator Under Radiations: the Jason Family of Satellites. 31st European Frequency and Time Forum (EFTF/IFC), Besançon, F, July 10-13, 2017, paper 1063.
Samain A., Belli A. Exertier P., Rovera G.D., Time Transfer by Laser Link (T2L2) in non Common View between Europe and China. Proceedings of the 31st European Frequency and Time Forum (EFTF/IFC), Besançon, F, July 10-13, 2017, paper 1302.
Exertier P., A. Belli, E. Samain, U. Schreiber, Optical Time Transfer for accurate Clocks in Space, ACES workshop, 29-30 June 2017, Zurich, Switzerland.
Lemoine F., P. Exertier, A. Belli, N. Zelensky, DORIS USO Behavior revealed by Jason-2/T2L2, IERS Unified Analysis Workshop (UAW-IERS), 10-12 July 2017, Université Paris-Diderot, Paris, France.
Belli A., P. Exertier, Test de l'isotropie de la vitesse de la lumière à partir du Transfert de Temps une voie par Laser, SF2A-GRAM Atelier de Physique Fondamentale, 4 Juillet 2017, Paris.
Belli, A., Exertier P. et al., Suspected time errors along the satellite laser ranging network and impact on the reference frame, submitted to G2.2, EGU General Assembly, 23-28 April 2017, Vienna, Austria, EGU2017-9405
Belli, A., Exertier P., Samain E., Courde C., Vernotte F., Jayles Ch., Auriol A., Characterization of an ultra stable quartz oscillator thanks to Time Transfer by Laser Link (T2L2, Jason2), EFTF & International Frequency Control Symposium (EFTF/IFC) 2015, Denver Colorado, US, April 13-17 2015.
Belli, A., Exertier P., Samain E., Courde C., Vernotte F., Synchronization of Geodetic Observatories thanks to Time Transfer by Laser Link, UAI General Assembly 2015, Honolulu Hawai, US, 3-14 August 2015
Exertier P., Samain, E., Belli, A., Courde, C., Guillemot, Ph. (2014) Time Transfer by Laser Link (T2L2) : A way to synchronize laser ranging observatories at the ns level, Invited Paper 3083, Proccedings of the 19th International Laser Ranging Workshop, Annapolis, MD, US, 26-31 October 2014.
Rovera G. D., Abgrall M., Courde C., Exertier P., Fridelance P., Guillemot P., Laas-Bourez M., Martin N., Samain E., Sherwood R., Torre J.-M. & Uhrich P., A direct comarison between two independent calibrated time transfer techniques: T2L2 and GPS Common Views, CPEM 2014, Rio De Janeiro, Brazil, 24-29 August 2014
Samain E., Laas-Bourez M., Courde C., Exertier P., Martin N., Torre J.-M., Guillemot P., Sherwood R. A., Appleby G., Rovera G. D., Abgrall M., Uhrich P., Fridelance P., A sub-ns comparison between GPS Common Viex and T2L2, EFTF 2014, Neufchâtel, Switzerland, 23-26 June 2014
Exertier P., Scientific Conferences, T2L2: analysis results and Scientific Applications, GRAM Assembly (INSU-CNRS), Bordeaux, France, 2-4 April 2014

Invited talks:

Exertier P., (2017) Scientific results of the Time transfer by Laser Link mission, NASA/Goddard Space Flight Center, Maryland, US, 21 March 2017.
Exertier P. (2016) Time Transfer by laser ranging ; current results and future progress, 20th Internat. Laser Ranging Workshop, Potsdam, Germany, 10-15 October 2015, sollicited paper.

Others:

Belli A., P. Exertier and E. Samain (2017), A Test of the One-Way Isotropy of the Speed of Light from the T2L2 Space Experiment, Proceedings of the SF2A 2017, C. Reylé et al. Eds, pp. 237-240, July 2017.

Pictures with captions (curve, photo, scheme …):

Télescope laser MEO, Observatoire de la Cote d'Azur

Schéma de principe de datation d'évènement à la station