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RTO AGARDograph 160
Flight Test Instrumentation Series – Volume 20

SCI-033

Optical Air Flow Measurements in Flight

(Mesures optiques de l'écoulement aérodynamique en vol)

This AGARDograph has been sponsored by SCI-122, the
Flight Test Technology Task Group of the
Systems Concepts and Integration Panel (SCI) of RTO.

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- AVT Applied Vehicle Technology Panel
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- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

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RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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AGARDograph Series 160 and 300

The Systems Concepts and Integration (SCI) Panel has a mission to distribute knowledge concerning advanced systems, concepts, integration, engineering techniques, and technologies across the spectrum of platforms and operating environments to assure cost-effective mission area capabilities. Integrated defence systems, including air, land, sea, and space systems (manned and unmanned) and associated weapon and countermeasure integration are covered. Panel activities focus on NATO and national mid- to long-term system level operational needs. The scope of the Panel covers a multidisciplinary range of theoretical concepts, design, development, and evaluation methods applied to integrated defence systems.

One of the technical teams formed under the SCI Panel is dedicated to Flight Test Technology. Its mission is to disseminate information through publication of monographs on flight test technology derived from best practices which support the development of concepts and systems critical to maintaining NATO's technological and operational superiority. It also serves as the focal point for flight test subjects and issues within the SCI Panel and ensures continued vitality of the network of flight test experts within NATO.

These tasks were recognized and addressed by the former AGARD organization of NATO in the form of two AGARDograph series. The team continues this important activity by adding to the series described below.

In 1968, as a result of developments in the field of flight test instrumentation, it was decided that monographs should be published to document best practices in the NATO community. The monographs in this series are being published as individually numbered volumes of the AGARDograph 160 Flight Test Instrumentation Series.

In 1981, it was further decided that specialist monographs should be published covering aspects of Volume 1 and 2 of the original Flight Test Manual, including the flight testing of aircraft systems. The monographs in this series (with the exception of AG 237, which was separately numbered) are being published as individually numbered volumes of the AGARDograph 300 Flight Test Techniques Series.

At the end of each AGARDograph 160 Flight Test Instrumentation Series and AGARDograph 300 Flight Test Techniques Series volume is an annex listing all of the monographs published in both series.

Optical Air Flow Measurements in Flight

(RTO AG-160 Vol. 20 / SCI-033)

Executive Summary

Optical measurements are increasingly becoming a part of measurement techniques in airborne systems. It has become important to avoid protuberances on military aircraft designed for stealthy radar characteristics. Optical measurement systems offer the possibility of accurate airspeed measurements that do not increase the radar cross-section. Although the experience base is small, cost studies show that substantial savings are possible for military applications. Applications of optical air flow measurements on highly maneuverable aircraft are expected to provide much more reliable information in regions of the flight regime where unacceptable measurement uncertainties plague conventional probe-based techniques.

Furthermore, with optical methods, the velocity of air masses at some distance from the aircraft can be measured. This feature can be utilized for several purposes. Air data measurement on helicopters beyond the rotor downwash and on first flights of prototype aircraft are improved. Warnings for turbulence and wind shear in front of the aircraft can be generated for prevention of engine unstarts and for improvement of flight safety. The researcher can study the atmosphere without flying through the air mass under study. The researcher measuring the air at very small distances from the aircraft learns about aerodynamics, and can be confident that the measurement process does not disturb the condition being measured. Parachute drop accuracy can also be improved.

The purpose of this AGARDograph is to bring attention to optical technology as it is currently being utilized in flight systems and to mention future technology prospects. The reader will become familiar with the vocabulary, components, and techniques in using optical components in airborne systems. Applications for airborne optical systems and case studies are also discussed.

Mesures optiques de l'écoulement aérodynamique en vol

(RTO AG-160 Vol. 20 / SCI-033)

Synthèse

Les mesures optiques font de plus en plus partie des techniques de mesure utilisées dans les systèmes aéroportés. Il est désormais important de s'assurer que les avions militaires conçus pour la furtivité ne comportent pas de protubérances. Les systèmes de mesure optique offrent la possibilité d'exécuter des mesures précises de la vitesse aérodynamique sans augmentation de la surface équivalente radar. Bien que l'expérience acquise dans ce domaine soit limitée, des études de coûts ont montré que des économies de coûts considérables seraient réalisables dans le cas d'applications militaires. La mesure optique de l'écoulement aérodynamique appliquée à des aéronefs très manœuvrants devrait fournir des informations beaucoup plus fiables sur des parties du domaine de vol pour lesquelles les techniques à base de sondes actuelles sont entachées d'incertitudes de mesure.

En outre, les méthodes optiques permettent de mesurer la vitesse de masses d'air à différentes distances de l'aéronef. Cette caractéristique peut être mise à profit de différentes façons. L'enregistrement des données aérodynamiques est amélioré, tant pour les hélicoptères, en ce qui concerne le domaine de vol au-delà de la zone de déflexion vers le bas du rotor, que pour les premiers vols d'avions prototypes. Des signaux d'avertissement peuvent être générés en cas de détection de turbulence et de cisaillement du vent à l'avant de l'aéronef, afin d'éviter les décrochages et d'améliorer la sécurité en vol. Le chercheur peut étudier l'atmosphère sans traverser la masse d'air à l'étude. Lorsqu'il mesure l'écoulement d'air à des distances très rapprochées de l'aéronef et s'informe sur l'aérodynamique, il peut avoir la certitude que le processus de mesure ne perturbera pas le milieu étudié. La précision lors de parachutages peut également être améliorée.

Cet AGARDographe a pour objectif d'attirer l'attention sur les technologies optiques telles qu'actuellement employées dans les systèmes de navigation et d'évoquer les perspectives technologiques futures. Le lecteur pourra se familiariser avec le vocabulaire, les composants et les techniques d'intégration des composants optiques dans les systèmes aéroportés. Certaines applications pour systèmes optiques aéroportés et des études de cas sont également présentées.

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The authors are indebted to the many researchers in the field of optical measurements who hosted fact-finding visits, willingly sharing their experience, and provided comments on the narrative text to improve the technical accuracy and the readability of the final product. Although there are many reference publications on optical theory, applying this theory in the flight environment requires knowledge from many other disciplines, most notably aeronautics, meteorology, atmospheric science, aerodynamics, signal processing, and mechanical design. A store of experience (in many cases experience in what did NOT work) is very valuable to the researcher in avoiding unproductive activities that do not yield useful results. The authors have incorporated comments reflecting the experience of many contributing researchers to provide guidance for the design of new systems that can acquire reliable optically based measurement in flight. Mr. James Meyers from NASA Langley Research Center, Hampton, Virginia was particularly helpful in providing information and feedback on the text. Others providing information and comments were:

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Nomenclature

Acronyms

A/D	analog to digital
ACLAIM	airborne coherent lidar for advanced in-flight measurements
AGARDograph	Advanced Guidance for Alliance Research and Development volume
ALEV	Anémomètre Laser en Vol (Airborne Laser Velocimeter)
ANSI	American National Standards Institute, District of Columbia, US
AoA	Angle of Attack
AoS	Angle of Sideslip
ATADS	Advanced Technology Air Data System
CLIO	circle-to-line image optic
CLR	coherent laser radar
CTI	Coherent Technologies, Inc., Lafayette, CO, US
CW	continuous-wave
DGV	Doppler global velocimetry
DLR	German Aerospace Center DLR, Germany
DSP	digital signal processor
EADS	European Aeronautic Defence and Space Company
EML	enhanced mode lidar
FFT	fast Fourier transform
FL	flight level
IR	infrared
ISL	Institut Saint-Louis (French-German Research Institute), France
JOADS	joint optical air data system
L2F	laser two-focus anemometer
ladar	laser detection and ranging
laser	light amplification through stimulated emission of radiation
LDA	laser Doppler anemometry (a type of dual-beam Doppler)
LDV	laser Doppler velocimetry (a type of dual-beam Doppler)
LED	light emitting diode
lidar	light detection and ranging
LIF	laser induced fluorescence
LTA	laser transit anemometry

MEMS	microelectromechanical systems
MFLAME	multifunction future laser atmospheric measurement equipment
MOADS	molecular optical air data sensor
MPE	maximum permissible exposure
NASA	National Aeronautics and Space Administration, US
NCAR	National Center for Atmospheric Research, Boulder, Colorado, US
NLR	National Aerospace Laboratory, NLR, The Netherlands
PDV	planar Doppler velocimetry
PIV	particle image velocimetry
PMT	photomultiplier tube
RASP	real-time advanced signal processor
RTO	Research and Technology Organisation
SCI	Systems Concepts and Integration, one of seven RTO bodies
SL	sea level
SNR	signal-to-noise ratio
TAS	true airspeed
UN	United Nations
US	United States of America
USAF	United States Air Force
UV	ultraviolet
VFO	variable frequency oscillator
W	watt

Symbols

B	system bandwidth, hertz
c	speed of light, electromagnetic constant, 299,792,458 m/sec
d	distance between light sheets, meters
D	effective optical diameter of lens or telescope
ΔL	measurement volume length
Δt	time interval
e	energy
f	frequency
f	focal distance of collecting optic
f_D	frequency of intensity fluctuations on a detector that result from the Doppler effect
h	Planck's constant, 6.55×10^{-27} erg/sec

I	scattered light intensity
I_O	light beam intensity
$\bar{i}$	illumination direction, vector
$\bar{k}$	wave number, vector
$\bar{k}_s$	scattered wave number, vector component in direction s
L	range
nm	nanometer, one billionth of a meter
$\bar{o}$	observation direction, vector
P_T	transmitted light power
Q	technique for switching pulsed lasers
r	distance
R	effective optical radius of lens or telescope
s	distance between fringes
$\bar{v}$	velocity vector
v_{los}	velocity component in the line-of-sight direction (parallel to the light beam)
$v_\perp$	velocity component in the direction perpendicular to the line-of-sight
w_0	beam waist diameter
α	angle between beams in dual beam laser Doppler configuration
$\bar{\alpha}$	polarizability
β_π	atmospheric backscatter coefficient
δf	frequency change of light, Hz
$\delta\bar{k}$	wave vector change of light, caused by scattering
η	detector quantum efficiency
ν	frequency, Hz
λ	wavelength of light
θ	angle between laser beam axis and axis of light collection optics in DGV systems

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Measuring instruments
Meteorological instruments
Optical detection
Optical measuring instruments
Optical properties
Pressure measurement
Turbulence
Velocity measurement
Wind shear

14. Abstract

Providing an introductory practical overview of in-flight optical flow measurement techniques is the goal of this AGARDograph. This document is written for instrumentation engineer or research scientist having a need for making non-intrusive flow measurements on an aircraft. It is hoped that this document will be particularly useful for the technologist with a limited background in optical theory and limited experience in applying optical technology. The experience of the authors and well as numerous other workers has been infused to provide guidance to avoid expensive non-productive diversions that may occur when applying optical technology for the first time in the flight environment. This AGARDograph provides basic knowledge and techniques necessary to assess the applicability of optical measurements and to address effective optical measurement techniques in flight. Key aspects of optical measurements are discussed and the tradeoffs are identified as they are currently understood. Basic components of optical measurement systems are discussed and key requirements are identified. Specific systems designed for a variety of applications are discussed to provide insight for the reader.

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