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STATUS REPORT SOCRATES CONCEPT EXPLORATION EFFORT

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13. ABSTRACT (Maximum 200 words)

Project SOCRATES, development of a technology to detect hypothesized acoustic emanations from wake vortices, has been underway for more than four years. This report discusses several aspects of this project including the current level of knowledge concerning wake vortex acoustic properties, SOCRATES detection technology, and wake turbulence sensor deployment issues. Three recommendations are offered to restructure the programmatic approach of Project SOCRATES to reduce the high risk and high cost should the government decide to continue to pursue this program.

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PREFACE

As might be expected, all of the authors of this report have been deeply involved with the SOCRATES (Sensor for Optically Characterizing Ring-eddy Atmospheric Turbulence Emanating Sound) program at the Volpe National Transportation Systems Center (Volpe Center). Robert Rudis has been involved since the inception of the program at the Volpe Center in 1996 as Contracting Officer's Technical Representative (COTR) for the two contracts awarded to Flight Safety Technologies, Inc. (FST) and has also been the Volpe Center's manager of the SOCRATES program. Dr. Frank Wang recently undertook the task of processing and analyzing the microphone data that had been obtained from wake vortex acoustic tests conducted at Dallas/Fort Worth International Airport in July 2000, and the microphone data obtained concurrently with the SOCRATES test program at Langley Air Force Base. Anastasios Daskalakis became involved with the preparation for the Langley Air Force Base test program in May 2000 and assumed the duties of COTR in May 2001. He provided technical guidance and support for that test program.

The authors have expressed deep interest in the phenomenology of wake vortex acoustics, having heard sounds emitted from the direction of wake vortices in ground effect during other wake vortex test activities conducted under airport runway approach paths. They have had many discussions with colleagues concerning the sources of such sounds. Unfortunately, as their analysis concludes in this report, the SOCRATES Program, which is primarily a technology development program, is based upon a premise that is not sufficiently understood to support a technology development program. Therefore, their recommendations propose that, if there is sufficient interest by the government to obtain a better understanding of the wake vortex acoustic phenomenon for possible application, that it be done as a rigorous scientific endeavor independent of any technology implementation.

In any case, the authors have enjoyed the relationship with FST and with the Lockheed-Martin technical staff that developed the SOCRATES laser technology and, in particular, with Dr. Richard 'Buck' Williams who is the manager of that effort. They have all benefited from being associated with this cutting edge technology.

The authors are indebted to the late George C 'Cliff' Hay who was the Federal Aviation Administration (FAA) Wake Vortex Program Manager during the early years of the SOCRATES program and who was instrumental in engaging the Volpe Center's participation in the effort. The authors are also indebted to George C. Greene, the current FAA Wake Vortex Program Manager, for his technical insight, managerial guidance, and for advocating and reinforcing a neutral, objective, and constructive skepticism in all technical pursuits.

Finally, the authors wish to express their gratitude to David Hinton and Frank Jones, the National Aeronautics Space Administration (NASA) Langley technical staff members who participated in the Langley test program and contributed to the content of this report.

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EXECUTIVE SUMMARY

The SOCRATES (Sensor for Optically Characterizing Ring-eddy Atmospheric Turbulence Emanating Sound) sensor concept envisions a large array of laser beams, with each beam acting as an array of directional microphones, and sophisticated signal processing software. Together, the hardware and software would be used to locate and track a variety of atmospheric hazards by distinguishing the sound produced by the hazard from the background noise at ranges from less than a kilometer to 50 kilometers or more depending on the hazard type. There has long been a lot of skepticism within the scientific community that this concept will work as envisioned. It is important to note that no one has ever built a full SOCRATES sensor so there is no data to confirm or dispute many of the SOCRATES claims. Testing to date has occurred with sensor arrays having two and four laser beams. These arrays have much less range and sensitivity than a full sensor array with many laser beams and should not be judged as a full sensor. Development and testing of a full sensor is estimated to cost “tens” of millions of dollars and would be expected to take a decade or more to develop.

The application of SOCRATES for wake turbulence detection was based on the fundamental premise that wake vortices emitted unique consistent acoustic signals that could be reliably distinguished from background noise in an airport environment. There is a dearth of literature on this subject since it is an area where research is in its early stages.

Beginning in FY 1997, Congress directed the Federal Aviation Administration (FAA) and, subsequently, the National Aeronautics Space Administration (NASA) to evaluate the SOCRATES technology in a program that included a test program at Kennedy International Airport (JFK) and ended with tests at NASA Langley in FY 2000.

Two series of aircraft measurement tests were conducted by the FAA to evaluate the premise using the SOCRATES technology. The first test was at JFK, using a 2-beam system, and was exploratory in nature as little was known about what to expect from the results. At JFK, aircraft flew over the sensor at an altitude of about 200 feet. Typically, no signal was obtained until the wakes were very close to the ground. After considerable difficulty, one noise track (out of many overflights) was identified which was confirmed to be due to wake turbulence by an independent vortex tracking system.

The second test was conducted jointly with NASA at the NASA Langley Research Center. NASA’s B-757 aircraft was used to fly over a 4-beam sensor at altitudes of about 300 and 600 feet. The vortex locations were validated by an independent sensor. For 11 flights, the SOCRATES sensor was able to identify noise coming from the direction of the wake. Although it was apparent that significant progress had been made in both hardware and signal processing since the JFK tests, for some of the runs, the sensor was unable to distinguish a wake generated 300 feet overhead from background noise due to wind. It is not clear at present if this is due to sensor characteristics, lack of a unique signature caused by wakes, or something else. However, these results call into question the entire premise of reliably detecting atmospheric hazards, and particularly wake vortices at large distances by the sound which they produce.

It is clear at this time that the technology cannot be tied to any airport development program planned for near-term operational implementation, without unacceptable risk. Considerable additional basic research is required to determine if there is any further potential for using the SOCRATES technology for detecting atmospheric hazards.

The following actions are recommended based upon the detailed discussions that are presented in the body of this report concerning the SOCRATES technology and a review of the current state-of-understanding relative to the acoustic properties of wake vortices.

Recommendation 1

Any further development of SOCRATES sensor technology and other candidate systems dependent upon the hypothesized wake vortex sound-generation phenomenon should be deferred until such time as there is a strong, well-established phenomenological basis for their further development.

Recommendation 2

If there is any interest by the government in pursuing phenomenological research; that is, determining whether wake vortices emit unique, consistent acoustic signatures, for possible application to wake vortex detection, the investigation should be initiated and conducted prior to the development of any potential passive acoustic wake vortex sensor.

Recommendation 3

The FAA and NASA should cooperatively develop a set of requirements for an operational wake vortex sensor to support the development and deployment of a wake turbulence system for mitigation of wake turbulence constraints on airport capacity.

LIST OF ACRONYMS

ATC	Air Traffic Control
AVOSS	Aircraft Vortex Spacing System
CD-ROM	Compact Disk Ready-Only Memory
COTR	Contracting Officer’s Technical Representative
CW	Continuous Wave
DLR	German Aerospace Center
FAA	Federal Aviation Administration
FST	Flight Safety Technologies, Inc.
FY	Fiscal Year
IF	Instrument Flight Rules
JFK	Kennedy International Airport
LAFB	Langley Air Force Base
LaRC	NASA Langley Research Center
LIDAR	Light Detection and Ranging
MITLL	Massachusetts Institute of Technology Lincoln Laboratory
NAS	National Airspace System
NASA	National Aeronautics Space Administration
NOAA	National Oceanic and Atmospheric Administration
SFO	San Francisco International Airport
S/N	Signal-to-Noise
SOCRATES	Sensor for Optically Characterizing Ring-eddy Atmospheric Emanating Sound
SODAR	Sound detection and ranging
SOIA	Simultaneous Offset Instrument Approach

LIST OF ACRONYMS (cont.)

TIM	Technical Interchange Meeting
VAS	Vortex Advisory System
VFR	Visual Flight Rules
Volpe Center	Volpe National Transportation Systems Center

1. INTRODUCTION

The development of the SOCRATES (Sensor for Optically Characterizing Ring-eddy Atmospheric Turbulence Emanating Sound) concept has reached a point where a discussion of its current status is essential in order to better evaluate its potential as a wake turbulence sensor. This document is being prepared as an interim report at a key juncture of the 4-year SOCRATES development effort. The body of this report is a discussion of the various issues involved in this concept assessment and deals with the present level of knowledge and understanding of those issues. The purpose is to provide an assessment of what has been accomplished, what has been learned, and recommendations as to the approach to be taken in the future with respect to further efforts in the development of this concept.

There have been two major deliverables received thus far concerning the SOCRATES work under the previous and current contracts between the Volpe National Transportation Systems Center (Volpe Center) and Flight Safety Technologies, Inc. (FST). Included as Appendix 1 is a CD-ROM containing a copy of the Phase 1 FST final report, which describes the results of the SOCRATES sensor development and subsequent testing at Kennedy International Airport (JFK) conducted during May 1998. Also, on the same CD-ROM, is a copy of the Phase 2 Langley test program final report. The Phase 2 effort was the follow-on to the Phase 1 work and includes enhancements to the SOCRATES laser array and the results of the Langley Air Force Base (LAFB) test program conducted during December 2000. Appendix 2 is a compendium of comments on the Phase 2 Langley test program final report. This information is being provided to allow interested readers with technical and administrative perspectives, to review the material delivered including this SOCRATES status report and evaluate the current status of the work for themselves.

This report is not a detailed technical analysis of the final reports or other deliverables submitted thus far by the SOCRATES contractor. Instead, it is an evaluation of the programmatic approach taken to explore, understand, and exploit a concept for potential operational applications. This evaluation, based on the results to date, has led to an alternative approach that considerably reduces the risk involved in developing a system based on a poorly understood phenomenon. The alternative approach is presented and discussed in Section 8–Recommendations.

2. BACKGROUND

SOCRATES is a laser-based acoustic detection sensor. The SOCRATES sensor concept derives from work done for the Department of Defense for underwater applications.

It was originally proposed by FST in 1996 that this sensor would be capable of detecting, classifying, localizing, and tracking various natural, meteorological, and man-made atmospheric anomalies that pose hazards to commercial and general aviation. These aviation hazards include clear air turbulence, severe wind gusting along mountainous airstrip approaches, downdrafts producing windshears and microbursts, tornadoes, and mountain wind rotor, all of which are naturally occurring meteorological phenomena, and wake vortices which are generated by aircraft in flight. All of these phenomena, at one time or another, have proven to be hazardous.

The SOCRATES concept is based upon the hypothesis that each of the various natural, meteorological, and man-made atmospheric anomalies emit unique, consistent acoustic signatures in the near-infrasound region that are detectable at some distance (in some cases, kilometers), from the emitting source. The concept further assumes that the SOCRATES sensor will detect, in the local volume, the sound emitted by a remote source subject to normal atmospheric attenuation, effects of temperature gradients on propagation, and the delays caused by the speed of sound in the atmosphere. If this hypothesis is correct, early detection of distant and potentially hazardous meteorological anomalies might allow for avoidance measures by aircraft.

When the SOCRATES technology was first proposed to the aviation community, it was determined to be too immature and risky to achieve the priority required for funding in the FAA's research budget. It has been exclusively a congressionally mandated effort, called Project SOCRATES, during the fiscal years 1996 through 2000 inclusive. The program activities have been conducted by the Volpe Center under FAA- and NASA-earmarked funding.

The SOCRATES Phase 1 contract, concept exploration, was awarded to Flight Safety Technologies, Inc. (FST), on May 27, 1997 and, subsequently, a SOCRATES Phase 2 contract, concept evaluation, was awarded to FST on August 27, 1999. Both contracts were awarded non-competitively based upon SOCRATES concept patent applications filed by FST. The potential use of a successful SOCRATES sensor or its integration into other systems was not part of any requirements as described in the statements of work under the contracts awarded to FST. Both contracts were directed toward exploration of the SOCRATES sensor concept as it pertains to wake turbulence detection alone.

The Phase 1 contract has been completed and the Phase 2 contract is currently in force.

3. PRINCIPAL ISSUES

In attempting to ascertain whether a SOCRATES sensor, in the broad context, has a place within the National Airspace System (NAS), a number of issues must be addressed, if not as part of Project SOCRATES, than in a parallel effort independent of Project SOCRATES. There are three major issues.

3.1 PHENOMENOLOGICAL ISSUE

The first issue, and the most important, is phenomenological in nature and may be stated in the form of a rhetorical question:

1. Do wake vortices emit unique, consistent acoustic signatures?

3.2 TECHNOLOGY ISSUE

The next issue is absolutely dependent upon a strongly affirmative answer to phenomenological question 1 posed above. This issue is technological in nature and, again, may be stated in the form of a rhetorical question:

2. Is the SOCRATES sensor an effective technology for detecting wake vortex acoustic signals?

Even though the answer to question 1 is not known, most of the development of Project SOCRATES to date has been undertaken in support of the issue addressed in question 2.

3.3 OPERATIONAL ISSUES

Other issues remain but reside in a different and significantly more pragmatic arena, namely, terminal area air traffic control operations. The customary approach for developing a system for operational implementation would first involve development of requirements for the system. This would normally be done by the FAA operational organization, perhaps Air Traffic, in cooperation with other FAA organizations that specialize in various aspects of system development. In the case of SOCRATES, however, technological implementation was initiated without regard for specific operational requirements or considerations. As such, the next issue, which requires an unambiguous positive answer to issue question 2, also stated in the form of a rhetorical question, is:

3. Why should a SOCRATES sensor be integrated within the air traffic operations in the terminal area?

4. SOCRATES CONCEPT

The problem being addressed by SOCRATES is somewhat described by its acronym, Sensor for Optically Characterizing Ring-eddy Atmospheric Turbulence Emanating Sound. Consequently, the central purpose of Project SOCRATES is to develop ground-based and airborne sensors that are capable of providing detection, localization, tracking, and classification functions on distant sounds emanating from various weather and man-made anomalies that pose hazards to commercial and general aviation. These aviation hazards involve clear air turbulence, severe wind gusting along mountainous airstrip approaches, downdrafts producing windshears and microbursts, tornadoes, and wake vortices which are generated by all aircraft in flight. All of these phenomena, at one time or another, have proved to be hazardous.

The fundamental premise is that these phenomena emit unique, consistent acoustic signatures, and that these acoustic signatures are centered around frequencies located in the infrasound and extra low-frequency sound region. As such, the sound propagates over long distances relatively unimpeded by weather-related acoustic absorption or scattering losses. SOCRATES is focused upon exploiting these acoustic signatures of sounds emanated by and propagated from these distant acoustic sources. As a result of this, SOCRATES has the potential to provide an all-weather system capability. In a projection of the potential of the SOCRATES sensor, it was envisioned that it would be an umbrella sensor monitoring airport airspace for wake vortex presence out to a distance of 10 miles from the airport, or, in a very ambitious scenario, mounted on an aircraft for detecting clear air turbulence.

Technologically, the SOCRATES sensor array is based upon using a laser-based opto-acoustic approach which provides an alternative method of producing the equivalent of a large array of microphones. The laser-based, opto-acoustic approach makes use of refractive-index coupling and exhibits a response that has its main-lobe, spatial pattern symmetrically disposed in a disk normal to the optical paths of the lasers. The thickness dimension of the disk is shaped in the form of an optical line-array pattern. The signal amplitude response sensitivity of refractive-index coupling increases in direct proportion to frequency. Also, since rather long go/return optical path lengths are needed, a cooperative corner reflector is used for each laser making up the sensor array to effectively double the length of the optical path.

The initial opto-acoustic sensor array and the associated hardware and software including the data processing software were developed by Lockheed-Martin of Syracuse, New York under prior Department of Defense work. As envisioned, the sensor would require “tens” of beams to function as an operational sensor. The original 1-beam prototype concept exploration system was enhanced through the congressionally mandated program, Project SOCRATES as a 2-beam system for the JFK test program and further expanded to a four-beam system for the Langley test program. The feature extraction software development and the analysis of the data were conducted by Lockheed-Martin and FST.

5. SOCRATES PHASE 1 EFFORT

5.1 JFK TEST PROGRAM DESCRIPTION

Under Phase 1, Lockheed-Martin enhanced their opto-acoustic sensor array and designed and fabricated a 2-beam laser retro reflector system using the refractive index approach. This approach, as opposed to a backscatter approach, was chosen because of the relative ease with which it could be implemented quickly and the fact that Lockheed-Martin had significant experience in this area.

The most practical way to test a SOCRATES sensor system in the near term was to attempt to detect the acoustic emissions of wake vortices generated by landing aircraft at an airport because of the accessibility and dependability of wake vortices. An active FAA/Volpe Center Wake Vortex Test Site existed at JFK at the middle marker area of the approach path to runway 31R. This site is equipped with a 700-foot Windline for tracking vortices that have descended into ground effect. The Windline, which served as ground truth for the SOCRATES JFK test program, is located approximately 2,100 feet from the runway threshold and serves as a tracking sensor for wake vortices that are in ground effect. SOCRATES testing at JFK was limited to the sensing of wake vortices that have descended to the ground.

Five different configurations of a SOCRATES 2-beam system, oriented in different ways relative to the extended runway centerline, were used to acquire data on vortex noise. Supplementing the laser system, an array of microphones was also deployed. Vortex acoustic data was obtained for over 600 aircraft.

The test program was conducted during the period from May 22, 1998 to June 1, 1998. The draft Final Report, in one volume, was delivered in June 1999.

Of the more than 600 aircraft runs for which vortex data was acquired, detailed analysis was conducted on 30 runs. These 30 runs comprised all Boeing 747 and A320 aircraft that arrived before 0900 during the test period. The decision to concentrate on this subset of the total aircraft runs was based on:

- Consideration of the effort that would have been required to do the entire set,
- The conditions were most ideal at the time of the day,
- The strength of Boeing 747 wake vortices is high, and
- Previous experience that Boeing 747 vortices are noisy.

Results indicate that for 20 of the 30 aircraft runs, the laser data was contaminated by the interaction of the wake turbulence with the laser beams. This type of interaction also changes the index of refraction of the air thereby masking the change in the index caused by acoustic interaction.

Although both a microphone array and the laser sensor had detected what appeared to be vortex-related acoustic signals at a relatively low level, it is not clear precisely what the source or sources of the acoustics signals were. There are several possibilities: one likely possibility is the interaction of the vortex with the ground where induced turbulence may be the source of any sound. While this source of sound would be important in any sensor implementation, this is a secondary effect and is not a characteristic vortex acoustic signature.

Of all the data acquired during the JFK test program and processed and analyzed during the succeeding year, only one vortex track was both detected by the SOCRATES sensor array and validated by the FAA/Volpe Center JFK Windline. The Windline, however, did generate tracks for all the other wake vortices.

Due to the difficulty and time required to find even one validated vortex track, only a very small sample of the remaining data from the JFK test has been reviewed, and then only informally. No results from that informal review have been published.

The final report from FST for the JFK test program is included on the CD-ROM described in Appendix 1.

5.2 JFK TEST PROGRAM CONCLUSIONS

The JFK test program was a rapid development exercise to determine whether there was any basis to the hypothesis that wake vortices emit unique, consistent acoustic signatures and that the SOCRATES sensor array could detect them. The results indicated marginal detection, at best, using a 2-beam system.

6. SOCRATES PHASE 2 EFFORT

Under the SOCRATES Phase 2 effort, activities were funded to:

- Expand the JFK 2-beam system to 4 beams,
- Integrate automatic corner reflectors,
- Develop a calibrating sound source,
- Develop an off-line processor, and
- Conduct a joint test program with NASA at Langley Air Force Base (LAFB) to investigate detectability of wake vortices from formation at altitude to ground interaction.

6.1 LANGLEY TEST PROGRAM

Data collection activities for the SOCRATES test took place from December 6, 2000 to December 17, 2000. Data collection activities were predicated on the availability of the NASA Langley Research Center (LaRC) Boeing 757 which was being used to conduct other tests at another site but which was available for SOCRATES testing at departure and return. Data collection took place during four days from the two-week test period. Table 1 shows the period of flights the NASA LaRC aircraft flew for the evaluation of the SOCRATES sensor. A total of 22 flyovers occurred during the period of testing. Typically, the NASA aircraft would fly over the SOCRATES sensor suite prior to and at the conclusion of its primary flight missions. The aircraft flew at altitudes approximately 200 to 700 feet above the SOCRATES sensor array to provide an opportunity for the SOCRATES sensor to locate and track the wake vortices produced prior to the wake vortices entering ground effect.

Table 1, which was extracted from the Langley test program Phase 2 final report, is a summary of the test runs.

The NASA LaRC Pulsed LIDAR (light detection and ranging), which was the ground truth sensor, provided the location and track of the wake vortex for validation of the SOCRATES sensor detections.

A microphone array also was deployed by NASA LaRC acoustics personnel. These data are currently being analyzed by the Volpe Center.

The final report from FST for the Langley test program is included on the CD-ROM described in Appendix 1. A compendium of the comments received is in Appendix 2.

6.2 LANGLEY TEST PROGRAM CONCLUSIONS

The results from Table 1 indicate that the SOCRATES sensor detected and tracked wake vortices from 19 of the 22 fly-bys. However, of the 19 detections, only 11 were validated by the pulsed LIDAR, the ground truth sensor. For the remaining 8 runs, when the pulsed LIDAR was not operating, FST estimates of vortex path were developed using a simple vortex transport model. Although interesting, these 8 runs cannot be used as examples of success because of a lack of

Run Number	Date	Time of Array Flyover (GPS)		Data Availability						Aircraft (At CPA)		
		SOCRATES Acoustic CPA	Aircraft Track CPA	Aircraft	SOCRATES	Microphones	LIDAR	Scintillometers		Altitude (Feet)	Lateral Position (Ft.)(3)	Airspeed (Knots)
1	06-Dec-00	20:53:41	N/A	N	Y	N	Y	N		540.0 (2)	312 (1)	125 (2)
2	06-Dec-00	20:58:15	N/A	N	Y	N	Y	N		520.0 (2)	164 (1)	128 (2)
3	06-Dec-00	21:04:20	N/A	N	Y	N	Y	N		560.0 (2)	(-129) (1)	123 (2)
4	07-Dec-00	N/A	18:51:38	Y	N	Y	N	Y		265.1	195.00	135.0
5	07-Dec-00	18:59:31	18:59:35	Y	Y	Y	N	Y		276.1	198.00	134.3
6	07-Dec-00	19:07:09	19:07:11	Y	Y	Y	N	Y		296.5	160.00	134.3
7	07-Dec-00	19:10:59	19:10:59	Y	Y	Y	N	Y		291.5	134.00	134.6
8	07-Dec-00	19:14:47	19:14:47	Y	Y	Y	N	Y		273.1	150.00	135.4
9	07-Dec-00	19:22:41	19:22:41	Y	Y	Y	N	Y		290.0	140.00	134.6
10	07-Dec-00	19:31:34	19:31:34	Y	Y	Y	N	Y		296.6	127.00	132.6
11	07-Dec-00	23:03:47	23:03:47	Y	Y	Y	N	Y		557.0	187.00	119.8
12	07-Dec-00	23:08:59	23:08:59	Y	Y	Y	Y	Y		560.0	137.00	120.8
13	07-Dec-00	23:14:04	23:14:08	Y	Y	Y	Y	Y		562.4	193.00	122.4
14	13-Dec-00	N/A	16:13:07	Y	N	Y	Y	Y		259.3	187.00	151.0
15	13-Dec-00	N/A	16:17:42	Y	N	Y	Y	Y		262.5	198.00	142.2
16	13-Dec-00	N/A	21:35:09	Y	Y	N	Y	N		245.6	192.00	120.8
17	13-Dec-00	21:41:34	21:41:34	Y	Y	N	Y	N		252.6	198.00	119.9
18	13-Dec-00	21:46:03	21:46:03	Y	Y	N	Y	N		248.0	114.00	121.1
19	13-Dec-00	21:50:38	21:50:39	Y	Y	N	Y	N		250.4	265.00	121.7
20	13-Dec-00	21:54:56	21:54:57	Y	Y	N	Y	N		250.1	(-17.00)	120.6
21	13-Dec-00	N/A	21:59:09	Y	Y	N	Y	N		246.0	201.00	120.1
22	14-Dec-00	20:22:47	N/A	N	Y	Y	N	Y		N/A	N/A	N/A

Notes:

1. Estimated from acoustic signal at fly-over
2. From test logs
3. Relative to the center of the SOCRATES array

Table 1. Langley Test Program Test Run Summary

validation. By the same token, these 8 runs cannot be used as examples of failure for the same reason. Therefore, only 11 runs may be used to support the contention that SOCRATES detected and tracked validated wake vortices.

7. STATUS ANALYSIS

To date, the SOCRATES sensor, under test at JFK and Langley, has detected 12 validated wake vortex tracks from passing aircraft: 1 at JFK and 11 at Langley. In 4 years of developmental testing, a great deal has been learned in Project SOCRATES about opto-acoustic systems accompanied by advances in the technology and some insights have been gained concerning the methods of extracting acoustic signals from data obtained from the opto-acoustic system. However, at this pace, and even assuming that the answer to the question posed concerning issue 1, the phenomenological issue, is strongly affirmative, anything resembling a research sensor, that is, one that would be at the level of operation of a Windline or LIDAR, is more than a decade away (based on expert opinion). Deployment of a prototype operational system based on the SOCRATES concept is estimated to be even further in the future.

On the other hand, if the answer to the phenomenological question is unresolved, which is a reflection of the current status, then pursuit of this approach should be discontinued and another approach should be adopted. Clearly, if the result is negative, then further pursuit of any approach should be abandoned.

These issues will now be explored in more detail in the following sections and will follow the order as described in Section 3, Principal Issues.

7.1 PHENOMENOLOGICAL ISSUE

Although Project SOCRATES has been viewed as an applied research effort, this is not entirely correct. The SOCRATES laser sensor design to detect acoustic signals is indeed an application of a reasonably well-understood technology. Adapting this sensor for detecting acoustic signals emitted from atmospheric phenomena is applied research as long as the acoustic emanations of such phenomena and the mechanisms that give rise to these emanations are real and understood. The design of technology, particularly that being developed for potential operational use, must be designed specifically to the characteristics of the phenomenon being exploited. In Project SOCRATES, this has not been the case. Instead, the technological elements of the sensor, having been developed for some other purpose, were turned toward a phenomenon whose characteristics were hypothesized. Thus, the effort became one of continually modifying the technology in the hope that the hypothesized characteristics were correct. In fact, and as a direct result of the approach from the beginning of Project SOCRATES, there has been a shift of emphasis from the hypothesized infrasound characteristics to an audible band, and from an umbrella coverage philosophy to one where only relatively small areas of an airport can be covered. This has occurred because the originally hypothesized acoustic characteristics of wake vortices have not proven to be correct. With this degradation of expected operation, a SOCRATES sensor, even if it were to work at some level, would not be as effective a wake vortex sensor as a Windline or a LIDAR.

To embark on the development of a major new sensor, as indeed SOCRATES is, and then, during that development period, try to use it as the exploratory sensor for understanding and extracting fundamental characteristic acoustic properties from the wake vortices, properties that were hypothesized and upon which the sensor development is based, is a difficult approach at best.

The usual outcome of such an approach is that it becomes an exercise of continually trying to determine whether measurements derived are properties of the wake vortices or introduced by the sensor instrumentation and signal processing. The extraction of acoustic properties of wake vortices is an undertaking of some magnitude by itself, and should be pursued as a fundamental research effort. This means, in terms of a measurement program, controlled environments using well-understood basic instrumentation should be supported by an intensive effort to advance the analytic model of the acoustic properties.

The reason acoustic characteristics of wake vortices have been hypothesized is that there is a dearth of technical literature available on the issue. Sound generation from various aerodynamic phenomena is still an area of active research. However, efforts have been focused on engine exhaust noise, vortex and structure interaction noise, airframe noise, etc. In the aforementioned scenarios, ring or streamwise vortices generate the intense sound from the pairing process, violent collisions, or interaction with a solid surface. Acoustically, these situations represent more efficient sound generation processes compared to that of trailing streamwise vortices out of a ground effect. Conceptually, it may be foreseen that aircraft trailing vortices would not produce sound levels that would cause environmental or tactical concerns. For this reason, little is known about the acoustic signature of aircraft trailing vortices. The ongoing literature survey reveals that there have not been comprehensive investigations on the sound manifested by various fluid dynamics mechanisms present in aircraft trailing vortices. The following is an attempt to delineate this state of affairs and to provide a synopsis of the limited knowledge base.

In a survey paper on vortex sound generation, Powell[1] (1995) presented a theoretical "thought experiment" on how aircraft trailing vortices could generate sound. The trailing vortex system is modeled as a rectangular loop of line vortex. The far field sound pressure from such a vortex system is then expressed in a generalized integral form. Although the general solution was not worked out, it is evident that sound is produced when the vortex system is accelerating. Hence, the accelerating/decelerating of the trailing line vortex is identified as a sound production mechanism.

When diverging from the simplification of a line vortex that does not include a viscous core, the popular benchmark problem of Kirchhoff vortex in computational aero-acoustics represents a case relevant to aircraft vortex sound.[2] The Kirchhoff vortex has an elliptically shaped core rotating with a constant angular frequency. If the major and minor axes of the ellipse are set to be equal, the well known Rankine vortex is then produced. From the general Kirchhoff vortex sound theory, it is shown that a Rankine vortex would not emit sound. However, if the eccentricity of the ellipse is kept infinitely small but not zero, the normal velocity in the vortex exhibits a harmonic time dependence at twice the angular frequency of the vortex. Assuming the same harmonic time dependence for the acoustic pressure, the sound frequency emitted by the core will then be twice the angular frequency of the vortex core. The Kirchhoff vortex sound theory thus suggests that the acoustic frequency from this process would not exceed 30 Hz for the entire range of existing commercial transports. Following a similar argument, if a vortex column is oscillating about a fixed position in space (Saffman[3]), time dependent velocity variations within the vortex would likewise lead to acoustic emission. Hence, unless the vortex is perfectly round, both the angular velocity and vortex oscillation frequency would result in distinct peaks in the sound spectrum.

Zhang and Wang[4] (2001) considered the acoustic emission characteristics from a round viscous vortex in motion. The study suggests that a stationary axisymmetric vortex would not produce sound. Likewise, the same axisymmetric vortex descending at constant velocity would not emit acoustic energy. Sound is emitted only when a round vortex is experiencing accelerating/deceleration, and the resulting spectrum would be broadband with most of its energy concentrated at a frequency range below 200 Hz. Moreover, the best chance of detecting such vortex sound would be when the direction of observation is perpendicular to the path of the vortex.

By recognizing that when a vortex traveling in a real operational environment is never mathematically axisymmetric, it should experience shape changes due to different surrounding effects, and will have acceleration/deceleration in its trajectory. The final spectrum that results is likely to be a composite/superposition of the various idealized sound generation mechanisms. It should be kept in mind that the various aspects of vortex dynamics thus far examined would not produce the high pitch sound commonly heard in the field.[5] Before attempting to speculate on a cause, it is conducive to introduce the concept of absolute sound versus perceived sound. Frequency response of the human ears is different from those of devices such as microphones or SOCRATES sensors. Human ears have the tendency to amplify sound having frequencies between 1000 to 5000 Hz. Sound levels at these higher frequencies would seem much louder than they really are, even though their dB levels may be lower than those at lower frequencies. The frequencies identified in the various aforementioned theories are low, and would be easily missed by observers. The source for the higher frequency sound most often heard in connection with aircraft vortices is unknown. Since such a high frequency sound requires flow mechanisms oscillating at high frequencies, turbulence within or around the vortex would seem to be the most likely candidate. It is thus speculated that the sound generated by aircraft trailing vortices is generally broadband, whose lower frequencies are due to effects such as sudden change in trajectory/meandering and core shape. The higher frequency part commonly associated with our existing notion of "vortex sound" is likely to stem from turbulence, but the precise mechanism is yet to be identified.

Outside of the SOCRATES-related experimental efforts, it is worth noting the experience drawn from two recent flight measurement campaigns on acoustic signature of aircraft vortices, performed respectively by the National Oceanic and Atmospheric Administration[6] (NOAA) in 1999 and the German Aerospace Center[7] (DLR) in 2000. In the NOAA experiment, a single directional microphone was used. In the DLR campaign, a phased microphone array was employed. Results from both efforts indicate vortex acoustic contents to be concentrated below 200 Hz. The proper dissemination of the test results is underway according to the respective project leaders.[6,7] Note that the analysis of the SOCRATES data from LAFB tests was performed outside of the aforementioned frequency range, although the SOCRATES sensor is purported to perform well to as low as 100 Hz in its current state. It should be apparent that both analytically and experimentally, the level of existing knowledge on vortex sound is still rather academic.

What literature there is suggests that, under calm conditions, with wake vortices descending after formation, there may be little acoustic signal. It is posited that acoustic signals arise when the wake vortices encounter some sort of accelerating effect on the vortex such as turbulence cells in the atmospheric path of the vortices, variable winds, and interaction with the ground, in effect inducing turbulence within the wake vortex through deformation or reflection. Although it may be difficult to imagine a portion of the lower atmosphere completely devoid of turbulence or turbulence cells and thus producing absolutely silent vortices, the intensity of the sound may be a function of the degree of turbulence. In addition, the “silent” vortices would be most likely to have a long lifetime and therefore be the most hazardous. If this is true, then the acoustic signal will vary from effectively none at all to relatively loud and therefore, quite possibly too variable and unreliable to be an indicator of the presence of the vortex. In addition, extracting very low-level acoustic signals from ambient noise can be particularly difficult in a very busy airport environment.

7.2 TECHNOLOGICAL ISSUE

It is well known that a relatively simple laser-based opto-acoustic system can be used as a virtual microphone array to detect an acoustic signal and, with appropriate signal processing, the signal can be extracted from ambient noise. A multi-laser beam system can be beam-formed to locate and track a moving acoustic source. In addition, acoustic signal intensity can also be measured. The SOCRATES sensor is an example of such a system. Unfortunately, the implementation undertaken and tested thus far over the past 4 years has produced a system that has not been rigorously tested or proven to be effective or reliable in the detection of wake vortices. Despite costly expansion of the system in preparation for the JFK test program and, subsequently, the additional expansion of the system in preparation for the Langley test program, the results to date are not as good as those routinely obtained from other better understood sensors such as LIDARs and Windlines. It is envisioned that “tens” of laser beams would be required for equivalent performance. In its present state it is unlikely that, even if it were rigorously tested, the results would demonstrate a level of comparability with other available sensors.

Most of the concerns about the utility of the SOCRATES sensor arise out of a lack of understanding of the acoustic properties of wake vortices, as was discussed in previous sections. There are other equally serious concerns about the current maturity of the signal processing employed in attempting to extract signals from the ambient noise and the growth limits of the array and supporting instrumentation that would be necessary to improve its operation to a level comparable to other sensors.

The current SOCRATES sensor is composed of components that are not field qualified but which were selected to produce a timely working model for use under test conditions in the field. To continue this effort, the working model would need to be expanded in like manner and be subjected to considerably more testing until it reached a level of reliable operation consistent with the requirements that must be met before proceeding to development of an operational prototype.

In addition, for any wake vortex sensor to be of value, even as a research tool, the results of detection and tracking of wake vortices must be available within a short time (minutes or, at worst, hours) after creation of the vortices by the generating aircraft. Windlines and LIDARs do this in near real-time, with initial vortex data available in less than 30 seconds and then continuing through the entire tracking period. The availability of results from the SOCRATES sensor has been measured in months. This strongly suggests that considerable effort must be expended to have the SOCRATES sensor qualify as a research sensor. For an operational sensor, that is one that is used to control traffic, the requirement can be expected to be significantly more stringent.

Based on its performance to date and the still unresolved question of wake vortex acoustics, there is an exceptionally high risk in pursuing further technological expansion of this sensor to meet any useful wake turbulence detection criteria. It has fallen short of providing its worth in its current state relative to the resources expended and there is little basis for the contention that if the SOCRATES sensor were expanded to a larger array, detectability, the extraction of signal from noise, would improve considerably. The estimated cost of getting to the point where developing an operational prototype is considered, assuming the concept is viable, is in tens of millions of dollars and the projected time frame for development is more than a decade away if possible at all.

7.3 OPERATIONAL ISSUE

In undertaking the effort involved in developing a new wake vortex sensor, it is certainly prudent to look at the utility of such a sensor. There are currently a number of sensors that provide information concerning wake vortex characteristics and behavior. For example:

- Windlines, using propeller anemometers, are used to detect and track wake vortices that are in ground effect, but their obvious limitation is that they can only measure wakes near the ground.
- Pulsed LIDARs can be used to track wake vortices at relatively long distances (kilometers) and provide estimates of vortex strength, but their primary limitation is that they are not all-weather instruments and cannot penetrate clouds.
- Continuous wave (CW) LIDARs can be used to track wake vortices at distances up to approximately 200 meters, a region where wake vortices transition from an out-of-ground effect to an in-ground effect, and provide information concerning the vortex structure and estimates of vortex strength, but have the same limitations as pulsed LIDARs.
- Vortex SODARs (sound detection and ranging) can be deployed in a manner similar to Windlines and provide estimates of vortex strength and lateral position but are limited in vertical range to a few hundred feet and are subject to atmospheric effects that significantly affect sound propagation.

All of the above-described sensors were developed as research instruments. As presently configured, their practicality as operational sensors used to control air traffic is seriously limited for a number of reasons, including performance limitations, maturity, deployability, complexity of operation, and lack of requirements.

Even if there were such a thing as the perfect vortex sensor, it would have no use, by itself, within an operational environment under current instrument flight rules (IFR) aircraft separation standards. Although the intent might be to reduce separations, it is hardly likely since a vortex sensor will indicate only how the current vortex is behaving and does not predict how the next one will behave. Such a sensor might be used as a safety net for the current separation standards, but will encounter four challenges in such an implementation:

1. The current IFR separation standards have been shown to be safe, and a deployed sensor to validate that result would be perceived to be unnecessary.
2. Changing the current IFR separations would be a significant task, comprising validations studies and test programs, model development, and proof of safety.
3. It can lead to a reduction of capacity if, for current separation standards, it should indicate the presence of a vortex in the path of a following aircraft, thereby requiring a go-around.
4. It would be very difficult to integrate the output of such a sensor into controller operations without increasing performance requirements on the air traffic controllers or the complexity of the controller procedures.

If, on the other hand, a hypothetical perfect sensor were integrated with a system (as yet undefined) which provided a validated prediction of wake vortex behavior over a time span that would allow for smooth transition from one set of separation distances to another (based upon that prediction), it might serve as a continuing validation of the prediction and act as a safety net for those presumably rare circumstances when the prediction ran awry.

In addition, if a hypothetical perfect sensor were developed to provide not only wake vortex location but also vortex strength and a reliable correlation were developed between wake vortex strength and the hazard it represents to an encountering aircraft (a correlation that still eludes the aviation research and operational community), another dimension of the wake vortex airport safety equation could be explored.

Although there was an early attempt at developing a rudimentary system by the Volpe Center called VAS (Vortex Advisory System) that was based upon wind speed and direction and wind measurement sensors, a more comprehensive approach was developed by NASA LaRC called AVOSS or, Aircraft Vortex Spacing System. AVOSS, as an engineering model, was tested off-line as part of an extensive test program conducted at Dallas/Fort Worth International Airport between 1997 and 2000. The test program comprised a wide variety of meteorological sensors and included wake vortex sensors such as the NASA LaRC pulsed LIDAR, the MIT Lincoln Laboratory (MITLL) CW LIDAR, and the Volpe Center Windline. AVOSS, or more likely, some version of AVOSS may serve as the basis of an aircraft spacing system that could be implemented in the future. The intent is for aircraft spacings to be reduced from current IFR spacings when conditions allow, on the basis that the current IFR spacings are overly conservative under some meteorological circumstances. A sensor, whose requirements are also undefined, may play a role in that system application and serve for prediction validation and as a safety net. This possibility is currently being discussed within the FAA but no requirements have as yet been developed for such a system.

8. RECOMMENDATIONS

8.1 RECOMMENDATION 1

Based on the results obtained thus far from Project SOCRATES and the analysis provided in this report, we have concluded that the concurrent development of an extremely complex SOCRATES sensor technology and the fundamental investigation of the acoustic properties wake vortices using the SOCRATES sensor technology is an extremely high risk undertaking. The analogy in mathematics would be: one equation and two unknowns. There is serious doubt as to whether the phenomenon is sufficiently understood to warrant continuing the SOCRATES sensor development or any other candidate system for wake vortex applications based on the same phenomenon. Therefore, it is recommended that:

> Any further development of SOCRATES sensor technology and other candidate systems dependent upon the hypothesized wake vortex sound generation phenomenon be deferred until such time as there is a strong, well-established phenomenological basis for their further development.

8.2 RECOMMENDATION 2

It has become clear that there are some technical activities being conducted by others to investigate the acoustic properties of wake vortices. While there is not abundant literature on the subject, there is some interest in the area.[8] However, there does not seem to be a clear agreement on the acoustic characteristics of wake vortices other than some emphasis in the infrasound region of the acoustic band. It is recommended that:

> If there is any interest by the government in pursuing phenomenological research, that is, determining whether wake vortices emit unique, consistent acoustic signatures, for possible application to wake vortex detection, the investigation should be initiated and conducted prior to the development of any potential passive acoustic wake vortex sensor.

NASA would be a prime candidate to pursue this effort as a basic research program with support from universities and other government organizations. Phenomenon research should be pursued by conducting an analytical fluid dynamics modeling effort to ascertain whether there is any analytical basis to the contention that wake vortices emit unique, consistent acoustic signals and conduct test programs with wind tunnels and tow tanks and narrowly defined field tests using well understood sensors and processing algorithms for validation.

8.3 RECOMMENDATION 3

There are currently discussions underway concerning the possibility of developing wake turbulence mitigation solutions that address specific airport issues. Two approaches are being considered. One is an effort to modify procedures similar to that now underway at San Francisco International Airport (SFO) called SOIA, Simultaneous Offset Instrument Approach. This approach might very well find application at other airports with close-spaced parallel runways. A recent effort conducted by the Volpe Center at JFK investigated delays caused by concern for possible jet blast effects on arriving aircraft. This effect demonstrated that local application of wake turbulence separation criteria to a jet blast problem was excessively restrictive. The second approach is one where a relatively simple system would be deployed comprising a version of AVOSS and a wake vortex sensor to assist airports in safely recovering lost capacity. This approach would also, in all likelihood, require procedures modification. The links between the two approaches are obvious. In the latter approach, a wake vortex sensor of some type will be essential for continuing validation of mini-AVOSS predictions and as a safety net. In addition, wake turbulence mitigation schemes in the long term may also involve wake sensors that provide wake location and strength measurements. Therefore, it is recommended that:

> The FAA and NASA cooperatively develop a set of requirements for an operational wake vortex sensor to support the development and deployment of a wake turbulence system for mitigation of wake turbulence constraints on airport capacity.

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APPENDIX 1

JFK and LANGLEY TEST PROGRAMS DRAFT FINAL REPORTS CD-ROM

The accompanying CD-ROM contains copies of the JFK test program final report and the LAFB test program final report. The reports are presented in the form in which they were delivered to the Government. As such, they should be viewed as draft versions and accorded some allowances for any misspelling and grammatical errors and also for any lapses in clarity that might be encountered.

APPENDIX 2

LANGLEY TEST PROGRAM DRAFT FINAL REPORT REVIEWERS COMMENTS

On April 24, 2001, FST submitted the NASA Langley test report to the Volpe Center. The Volpe Center subsequently distributed the NASA Langley test report to technical and managerial personnel at NASA Langley and the FAA for a critical technical review of the SOCRATES sensor and its performance. On June 15, 2001, a Technical Interchange Meeting (TIM) was held at NASA Langley to discuss the SOCRATES sensor and the results of the NASA Langley test. Based on the submitted NASA Langley test report and the TIM, comments were submitted to the Volpe Center offering editorial and technical perspectives.

Comments received by the Volpe Center indicated that the premise of a unique, consistent acoustic signature produced from wake turbulence has not been validated in previous studies and remains unproven. Reviewers suggest initiating independent research efforts to study the premise of an acoustic signature being produced from wake turbulence before continuing with the development of the SOCRATES sensor. Another reviewer suggested that all the data collected from the NASA Langley test be processed and analyzed prior to commencing further development of the SOCRATES sensor.

Reviewers were encouraged that the SOCRATES sensor detected wake turbulence during the NASA Langley tests with verification from the LIDAR represented a significant improvement from the original JFK tests conducted in 1998. Further development of signal processing techniques would enhance the performance of the SOCRATES sensor.

The following part of this Appendix lists the unedited technical comments received by the Volpe Center from various reviewers.

Reviewer #1

Figure 31: Why are the four beams, located very close together, so different?

Section 3.5.3: Why use only two of four beams for localization? Shouldn’t all four give less ambiguity?

How are cross-correlation results (e.g., Figure 32) transformed into wake elevations angles (e.g., Figure 40)?

Section 3.5.5 & Figures 44-46: When the aircraft is past the location of the beams, then its elevation angle in the X-Z plane would seen to be irrelevant to the response of the beams. The aircraft noise will be coming essentially from the end of each beam and have no coherent effect over the beam.

Reviewer #2

While the premise of the SOCRATES experiments was valid - Is there a robust acoustic signature from a wake vortex that can be detected? - there was some discussion of the emphasis of the approach. With microphone data existing, NASA preferred that data be analyzed first, to determine the signature of the vortex noise, before attempts at tracking and discussions of relative success were held. The analysis of the microphone data is, in their opinion, a priority next step. The use of Kalman filters, etc. was argued as inappropriate without prior knowledge of the signature to ensure there wasn't an incorrect masking bias in the filter.

Two competing characteristics of SOCRATES exist. One is that an unambiguous location (slant angle) can be surmised only in far-field ranges (2+nmi). The other is that the signal strength decreases with distance. Left to their own imagination, Lockheed-Martin/FST might well focus research efforts on improving signal/noise ratios with a goal of improving the range of the sensor. Specifically, Lockheed-Martin repeatedly referred to use of SOCRATES at 3 nmi and possibly sensing "up the glide slope." A quick look at operations tells me that, as an acoustic sensor detecting 3 miles away, the sensor is giving me information on an event that occurred 20 seconds earlier. In an ATC/radar or VFR environment, 20 seconds is an awfully long time - probably too long to provide any benefit. Some analysis of controller behavior and system latency behavior will help determine the limits of acceptable sensing distances, given speed of sound. Such analysis may yield a specific role for SOCRATES, or may ultimately tell us that sensing wake strength (given location ambiguities in the near-field) is the appropriate sensor application. Such results would provide direction for near-term research of SOCRATES.

Reviewer #3

The review seemed to indicate that the SOCRATES team is looking for a signature. The presentations included different methods of data reduction with little agreement among the methods. I do not believe that current results indicate that SOCRATES is a viable sensor for any safety related sensor.

My suggestion: if there is to be future funding of SOCRATES, it would be to concentrate on current data sets. All LAFB data including all SOCRATES and all microphone data should be reduced.

SOCRATES and NASA and FAA should look at this data and determine if an acoustic signal is available from vortices and if that signal is robust enough to be used in an all-weather safety related system.

I would suggest that in developing an understanding of that signature, all the data available from all sensors be provided.

If a signature is found, SOCRATES should develop tracking software based on that signature and SOCRATES should demonstrate that this software can track using the stored SOCRATES data sets with no input from other sensors.

Reviewer #4

Lockheed stated that the assumed wake vortex signal is broadband and that the low frequency range was essentially system noise, and therefore, not useable. However, Flight Safety Technologies using wavelet analysis made the system noise data look like vortex data. Obviously, the two companies did not examine each other's data. This is clearly reflected in the report. They need to agree on good data versus noise.

Although they found wake data in 17 out of 19 runs, Lockheed presented only Run #13 in the report. For this run it was suggested in Figure 15 (text calls it Figure 23) that the aircraft noise lasted ±10 seconds from the peak; it looks more like ±20 seconds. It was assumed that the data from 80-90 seconds is wake data (Figure 23), whereas it looks like the tail of the aircraft noise. It seems to me that the first step in the analysis is to study the aircraft noise for the 21 runs to determine the decay time of the pulses (and perhaps as a function of wind speed). The microphone data may help with this question.

As a minimum, I would like to see a plot like Figure 15 (text calls it Figure 23) for all the runs to determine whether the small variations in the plot outside of the aircraft pulse is really due to vortices or the background noise and wind variations.

The only data presented at the meeting that looked promising was Bob Cooperman's correlation data. It should be analyzed further and included in the final report.

Reviewer #5

At the start of one of the presentations, there was a listing of premises (which I will paraphrase since I have no copies of any of the presentations):

1. Hazardous atmospheric conditions (e.g., wake vortices) make sound,
2. The sound is loud enough,
3. The sound is distinctive, and
4. SOCRATES laser sensors will detect it (and, implicitly, with S/N to allow identification, localization, and tracking).

Nothing in any of the presentations convinced me of the validity of any of the premises. I'm not saying the premises are untrue, only that the evidence presented, in the absence of reasonable supporting theory, is neither consistent nor convincing. There was discussion of frequencies that ranged from infrasonic to several thousand Hertz, but no indication of sound-generating mechanisms other than some vague hand waving about shedding vortices.

After the premises there was a list of issues including S/N ratio and operational constraints. Following that was a delineation of the approach to the problem that ended with expanding the system and looking at (or listening for?) hazards other than vortices. With a focus on the development of hardware, implementation at specific airports, and operational considerations, I fear that there has not been enough examination of whether there is any reason to believe that this kind of a system can work. Before continuing with any more operational experiments, and even before continuing with any system development other that fixing known inadequacies, I think the premises should be revisited with a much more critical eye.

If, for example, the first premise is true only part of the time, then no system of this nature, regardless of its sophistication, can detect a vortex more than part of the time. Without a firm theoretical basis, it would be impossible to know the conditions under which the first premise is invalid. Failure to detect an acoustic signal would then mean either no vortex, or a quiet one.

A better theoretical understanding of wake vortex generation, evolution, consolidation, and interaction with the atmosphere must be developed to better understand the likelihood of acoustics generation as well as the character of whatever sound is generated in order to determine the efficacy of any acoustic method for detection, identification, localization, and tracking of airplane wake vortices.

SOCRATES sounds more like a solution in search of a problem than a thoughtfully considered alternative approach to a known problem.

Reviewer #6

Page 1: “The SOCRATES approach is predicated on wake vortices generating a unique acoustic signature that can be used to determine the location of the vortex sound source.” To my knowledge, this very fundamental premise has not been conclusively verified either theoretically or experimentally, at least not in the open literature. The report itself also stated that their own theoretical modeling effort is not complete. I personally believe in making fundamental studies on the various physical phenomena prior to building such a complicated system for complicated flight tests.

In spite of the aforementioned personal commentary, I find it encouraging that the report shows, if independently verifiable, that vortices might be tracked from cross-correlation of two SOCRATES beam signals. The tracking, as suggested in the report, requires that the two beams are in their optimal performances, and the interpretation of the cross-correlation contour may require some training/judgment. I presume that with improved signal processing, a more robust tracking capability may be obtainable. This may be an area the SOCRATES team could examine further. I personally do not understand why the cross-correlation levels are low, as one would expect relatively high correlation values everywhere, especially during aircraft fly-bys. This is a point that requires some explanation on the part of the SOCRATES team. Perhaps a word or two on the cross-correlation scheme would help.

However, the results (preliminary, because the report itself also hinted that further refinement in the post processing may be needed) from the latest SOCRATES tests do not seem to correlate very well with the circulation values from LIDAR measurements. I would suggest further investigation (preferably of the fundamental type) on how vortex acoustic signals may be related to aspects of the vortices of importance to airport operation. Circulation is a very rough characterization of a vortex and does not provide any details regarding the dynamics of the core, which is conceivably more important than the circulation evolution itself in sound production. With the available LIDAR data, instead of circulation, the rate of change of circulation may be attempted to correlate with vortex sound.

The experimental arrangement represents a vast improvement over that of the JFK tests for the fact that Langley AFB is a more controlled (acoustically) environment. The latest experiments also took away the ground effect as well as thrust reverse noise contamination concerns.

I have no comments on the description of the electronics. In fact I did not understand it.

On page 13, it was said that SOCRATES performed well for frequencies above 100 Hz, providing performance comparable to that of a line of microphones deployed over the sensing area, without the need to deploy hundreds of separate sensors. I was not aware of such a side-by-side comparison ever being made.

The experimental procedure described on page 26 requires the estimated position of the vortex to be tracked so as to minimize the false alarm. It appears that, if the beams are sweeping across the sky and cross-correlation can be used to first isolate the range of the elevation angles, the need to estimate the vortex position becomes unnecessary.

Page 28, regarding the prediction on vortex positions, the descent rate assumed appears low. For example, on page 56 where a LIDAR tracking is shown, if one were to follow the data from 9 seconds to 17 seconds, I get a descent velocity of about 5.6 ft/s by “eyeballing” the corresponding altitudes for those times. The typical landing weight and landing velocity of a 757 are 200,000 lbs and 152 mph, respectively. The classical elliptical wing estimate will provide a descent rate of 6.22 fps. What is the impact, if any, on the very conservative descent rate used in locating the vortex sound?

Related to the vortex trajectory model, why 3/8 was chosen?

The selection of a proper wavelet further illustrates the need for fundamental analytical modeling, computational simulations or laboratory experimental efforts. Without knowing what particular sound signature to isolate, selection of the correct wavelet seems to be a futile effort.

Page 58, Figs. 44-46, confusing.