BALLOON REMOTE SENSING PLATFORM FOR SITE SCALE WATER QUALITY MANAGEMENT OF MIXING ZONES[1]

ROBERT L. DONEKER

MixZon Inc., 1033 SW Yamhill St., #301, Portland, OR 97205 USA

TODD SANDERS

MixZon Inc., 1033 SW Yamhill St., #301, Portland, OR 97205 USA

Abstract. With USEPA SBIR program support, MixZon has developed a low cost, rapidly deployable, tethered helium balloon platform for aerial remote sensing of water quality in mixing zones. Mixing zones are limited regions in water bodies where the initial dilution of point-source wastewater discharge occurs. Mixing zones are an important regulatory component of National Pollution Discharge Elimination System (NPDES) permits within Total Maximum Daily Load (TMDL) water quality management programs.

We have demonstrated the technical feasibility of our platform to obtain spatial water quality data at site scales in riverine mixing zones using infrared and visual sensors. Our patent-pending platform measures outfall mixing and focuses on temperature as a dilution tracer. We have verified an easily deployable system that gathers continuous, real-time, site scale, geo-referenced mixing zone data for regulatory compliance. Currently available alternative aerial remote sensing platforms have limited availability, high costs, and long lead times. The cost of our platform is expected to be 1/3 to 1/10 the cost of the fixed-wing and helicopter alternatives, respectively.

Future developments will explore better methods for aiming sensors, techniques for data collection and processing at oblique camera angles, and development of data sets for hydrodynamic simulation model validation. Although our project focused on mixing of thermal plumes, the potential of our system to monitor mixing zones of other discharges types may be much more widespread, e.g. shoreline recreational exposure to pathogens from warm wastewater discharges, detecting groundwater inflow to surface streams, and analysis of thermal refugia habitat from tributary streams for endangered species management.

1. Introduction

Wastewater discharges in the US are required to have a National Pollution Discharge Elimination System (NPDES) permit. Ambient water quality standards need not be met at end of pipe if a mixing zone is allowed by the regulatory authority. A mixing zone is a limited region or area around the discharge where the initial dilution occurs. Dischargers must demonstrate sufficient dilution within the mixing zone to comply with water quality standards. Mixing zones are typically determined by mathematical modeling, however sometimes field dilution studies are required.

Water temperature itself is an important water quality parameter [1], and is of particular concern in the Pacific Northwest (EPA region 10) and the mid-western states (EPA Regions 5 and 7). In the Pacific Northwest, the limiting water quality standard for temperature is determined by several salmonid species under Endangered Species Act (ESA) protections.

Oregon DEQ recently proclaimed several thousand miles of streams in the project region to be in violation of temperature standards, and placed them on the 303(d) list for water quality violations. Water temperature alone accounts for over 75% of the stream miles on the Oregon 303(d) list [2].

In addition, water temperature can often be used as a “tracer” to indicate the dilution and spatial distribution of other important TMDL water quality parameters (e.g. sediment, coliform) that may occur within a mixing zone. Although our platform focuses only on detecting infrared (IR) temperature as a water

[1] This work supported by USEPA ORD SBIR research contract EP-D-07-086.

quality parameter, the potential of IR technology to monitor the fate and transport of other discharge constituents may be much more widespread.

1.1. *Aerial Sensors for Water Quality Monitoring*

Aerial IR sensors detect surface temperatures only. Thus, the variation in subsurface temperatures which may occur in deeper stratified flows can not be detected. Therefore, this project concentrates on remote sensing of shallow layer flows. We focused on mixing zones in rivers, where the shallow depth causes discharges to mix vertically rapidly, but can exhibit large downstream distances for full lateral mixing. Figure 1 illustrates mixing zones for surface point source discharges (in this case tributary streams) into a shallow river. Because of the shallow ambient flow, the discharges mix vertically rapidly so that both Figure 1A) cool and Figure 1B) warm discharge mixing zones, respectively, can be detected by surface thermal imagery. Although the discharges shown in Figure 1 are tributary streams, these could represent surface industrial point sources such as mine drainage or power plant cooling water [3].

Currently available alternative remote sensing platforms are not well suited for many mixing zone management issues [4]. Direct measurement of biophysical information such as temperature is dependent on the scale of the phenomena. To properly resolve riverine mixing zone spatial scales with the Nyquiest frequency limits requires resolution not readily available through space-based platforms and is limited to low-altitude helicopter or fixed-wing aircraft operations [5]. Both the helicopter and fixed-wind aircraft platform have enjoyed widespread successful application in remote sensing of the spatial distribution of surface water temperature values in mixing zones [6, 7]. However availability is limited, extensive operator training is required, and their costs are relatively high. Often, airborne platforms need to be reserved months in advance. Because of high costs and limited availability, helicopters and fixed-wing aircraft are not well-suited for rapid or routine deployment at a fixed location where hourly sampling may be required over a period of several days or weeks. Extended platform deployment scenarios are likely to be necessary in analyzing impacts of mixing zones in regulatory management.

1.2. *Advantages of Balloon Remote Sensing*

There are several advantages to using balloons or blimps as platforms for remote sensing data collection. One of the most significant advantages is that balloons can be deployed quickly and data collected immediately. Extensive operator training is not required. For instance, balloons could be sent up quickly to monitor chemical spills or accidental releases. Balloons may also be able to collect data that current helicopter or fixed wing cameras cannot. A balloon system could be deployed to monitor a specific site for hours or days which would be logistically difficult or impossible with current airborne imagery. Tethered balloons can be moved and relocated easily, providing a more flexible method to collect data. For instance, tethered balloons could be deployed on small boats in rivers to conduct water quality surveys over several stream miles.

Tethered balloon systems are limited in the height at which they can be located. Current FAA regulations limit most manned tethered balloon heights to 500 ft or less [8]. This altitude is sufficient for gathering data on most regulatory mixing zones. Also, tethered balloons are not suitable for deployment under high wind conditions. Tethered balloon may withstand winds up to 50 mph, however high winds may affect safety, payload capacity, and detection capability.

There are many examples where measurement of mixing zones by tethered balloon remote sensing would be beneficial in environmental management [6, 9-21]. The platform could be used to monitor spatial impacts from a contaminated groundwater source if a temperature differential exists. Often, domestic wastewater after treatment is warmer than ambient so thermal detection could be deployed to monitor impacts of treated sewage discharges on recreational areas.

In summary, this paper demonstrates the feasibility of tethered balloon remote sensing in water quality management. Our goal was to demonstrate the rapid deployment of a lightweight remote sensing platform to analyze water quality during critical low-flow conditions. Our platform provides the software and data

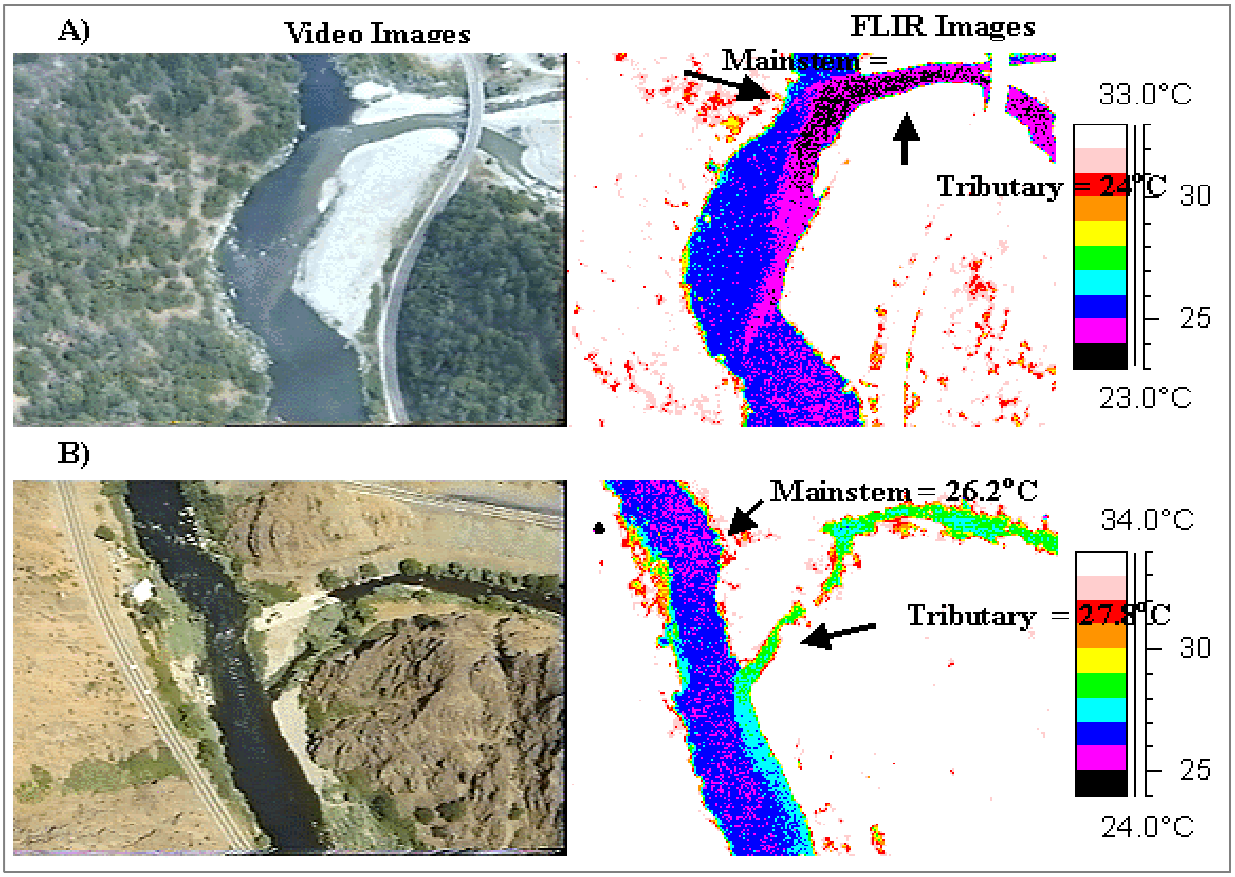

Figure 1. Examples of helicopter-based infrared remote sensing of mixing zones from a point source surface discharge. (Source: Oregon DEQ). Typical airborne infrared camera output consists of digital images covering approximately 100 x 100 meters with less than 1 meter of spatial resolution and ±0.5°C accuracy. Figures A) and B) show cool and warm tributary surface discharge sources respectively. Image Source: ODEQ.

management systems needed to document mixing zone water quality and support simulation model development and validation.

2. Remote Sensing Platform Development

The overall project objective was to demonstrate the feasibility of balloon-based IR remote sensing of water quality in mixing zones. Our approach was to construct and ground test the remote sensing platform before specification of the balloon needed to lift the payload. After we successfully ground tested the platform, we tested the balloon at first using a ballast weight equivalent of our remote sensing platform. This gave us an opportunity to evaluate balloon deployment and performance under various wind and environmental conditions. We then deployed the platform with the digital video and IR sensor to test and evaluate system operation.

The project culminated in a test deployment to evaluate the mixing zone of an industrial discharge on the Columbia River near Portland, Oregon in August 2006. The site was suggested to us by Oregon DEQ and USEPA Region 10 staff because it has mixing zone and Endangered Species Act (ESA) fish passage issues under low flow summer conditions. The project produced GIS data management tools for display of geo-referenced remotely sensed water quality in mixing zones on the reach scale. This software and data management system is intended to complement and support the development and validation of water quality simulation models [3, 24, 25].

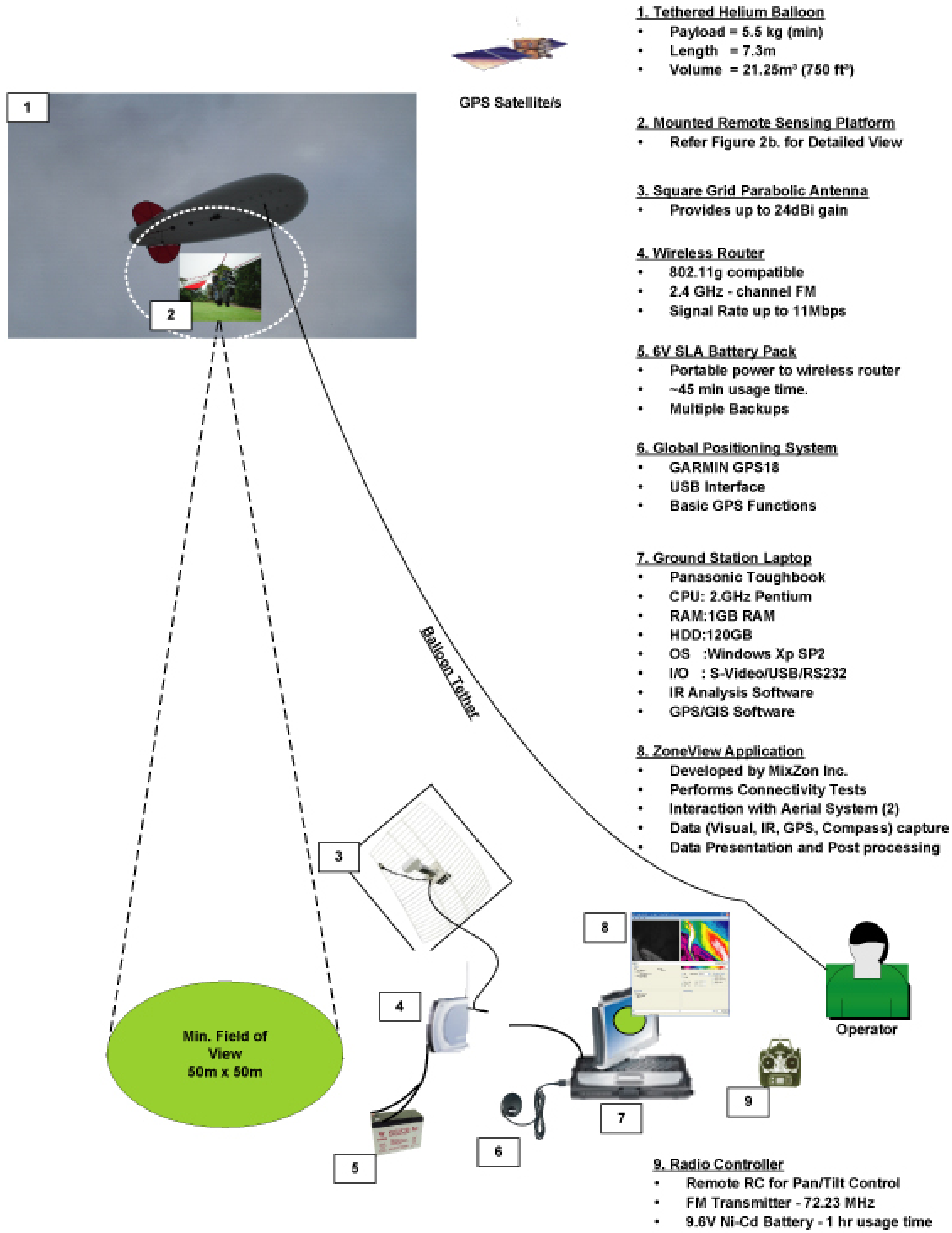

Figure 2a. Illustrative conceptual diagram of remote sensing system as developed and deployed in this project. US Patent Pending.

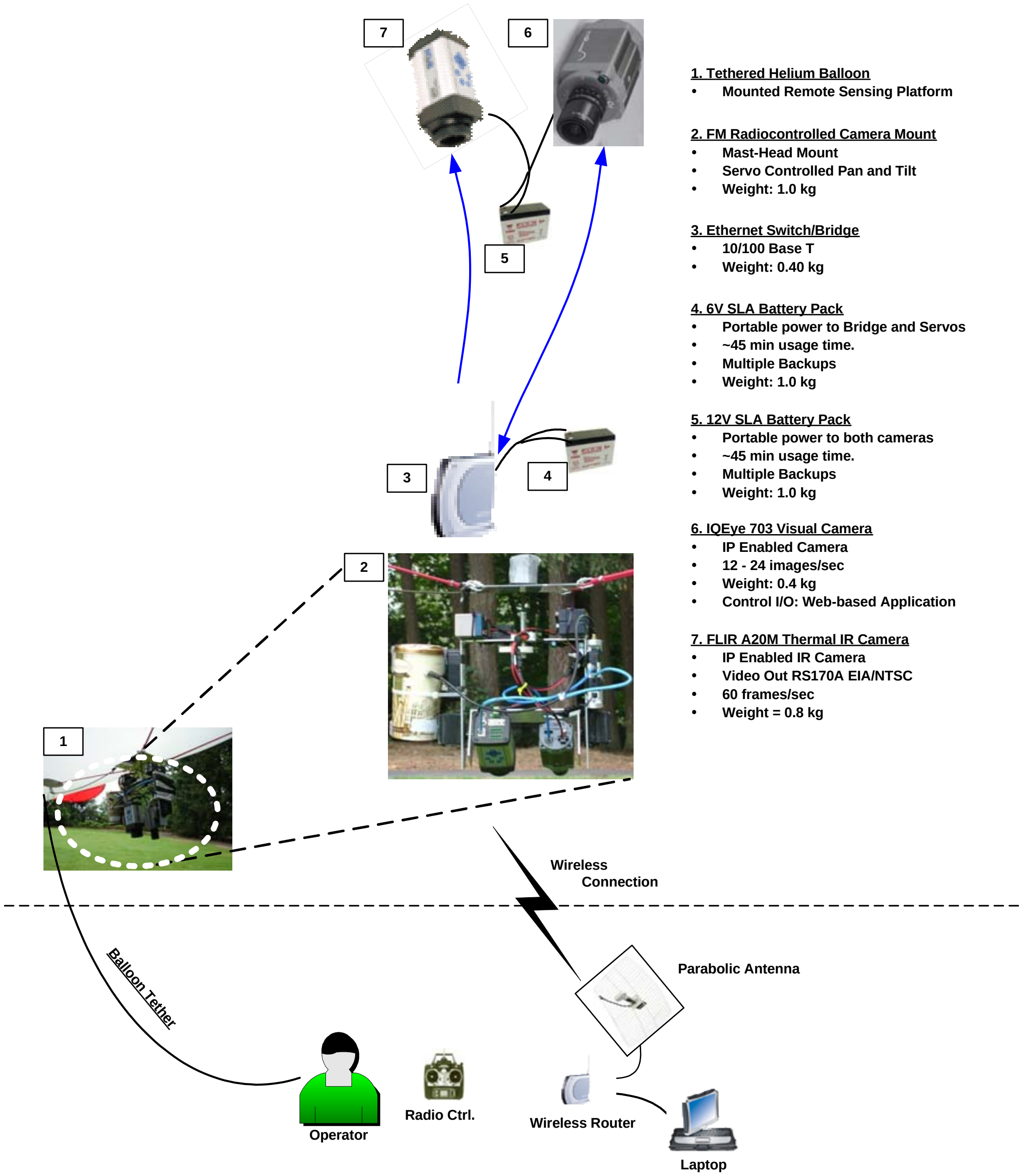

Figure 2b. Illustrative detail of remote sensing aerial platform as developed and deployed in this project. US patent Pending.

Figure 2a shows the conceptual schematic of our remote sensing system configuration. Our deployed remote sensing platform weighs less than 5.5Kg (12 lbs) and is deployable on a 7.5m x 2-m (24-ft x 6.5-ft) helium blimp. This size blimp is transportable in a 26-ft rental box truck. Figure 2b shows the detail of the remote sensing platform.

One of the technical challenges was to extend the range of available 802.11g wireless. On the balloon platform, we replaced the standard antenna on our wireless access point with a "cantenna" an antenna we constructed from a cookie can. The cantenna has a strong directional signal which we pointed vertically to the ground. We then used a parabolic square grid antenna and/or cantenna on the ground station. This configuration gave us the range and reliability needed to transmit data from the balloon platform.

2.1. *Remote Sensing Platform Deployment*

We were then able to transmit video images from the aerial balloon platform to a ground operator to correctly aim and monitor the IR camera on a radio remote control camera mount. This took some practice. However, eventually we were able to develop the skills to effectively aim the cameras.

We were able to demonstrate that our system with wireless 802.11g can transmit video and IR data from our remote sensing platform at elevations of 151-m to a ground station laptop computer using a battery-powered wireless router. The remote platform contained two lead-acid batteries which gave us about 50 minutes of deployment before we had to change batteries on the platform. All video and IR image data collected during deployment was tagged with time stamp and GPS position information and stored on the ground station laptop hard drive for later analysis.

For safety, we decided we would not deploy if wind speed was greater than 10 mph. Our blimp could have flow in winds of up to 30 mph, but we did not want to risk losing our equipment or causing an injury. In addition, we found that we needed a crew of 3 people to effectively manage a deployment. With additional practice and experience we think this could be reduced to 2 people. However, due to interest in our project, we often had 5-6 people available during deployment. We found that the best tether systems were composed of equipment used for rock climbing. We adapted a rock climbing belay harness and belay ring to control the blimp tether during deployment. We employed a garden hose reel to deploy and store our tether.

One of the greatest challenges was logistics for deployment. The field sites were remote enough to make retrieving missing items from the office impractical. Therefore, we developed extensive checklists to make sure we had all equipment necessary and in proper working order for deployment along with sufficient redundancy if a particular component failed.

2.2. *Image Processing*

Mixing zone water quality data are geo-referenced to high-resolution aerial photography. Aerial photography is available for purchase at a low cost for almost any area. These data are digital ortho-rectified images with high resolution. In most cases the pixel size is 1 ft. (0.3048-m), which is coarser than the data returned from our remote sensing platform IR and video cameras. At the maximum flight elevation, the IR and video cameras return Instantaneous Field of View (IFOV) spot sizes closer to 1.5 ft.

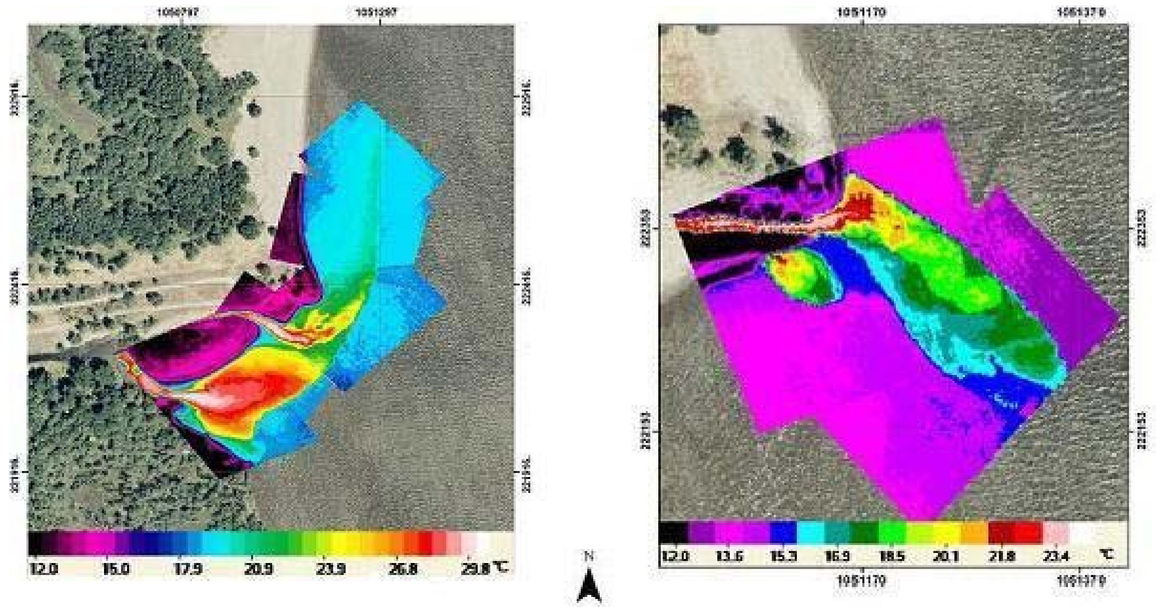

Figure 3. Geo-rectified thermal images taken by our tethered balloon platform. These images show a mixing zone from an industrial non-contact cooling water discharge (Q= $1m^3/s$; $\Delta T=10^oC$) taken by our remote sensing platform at an elevation of 500 ft. The discharge is configured as a surface channel or canal into the Columbia River. In image A, two plumes are visible during an ebb tide episode. The larger “southern plume” in image A is the result of a leak in the canal wall, with the “northern plume” being the intended discharge location. Image B shows the same site during flood tide after an attempt to repair the leak and extend the discharge location farther out on the point. The “northern plume” in image B is the intended discharge location, with a new canal leak visible as the small “southern plume” in image B. The new leak (southern plume) in image B is at the same location as the intended discharge before canal modifications as shown (northern plume) in image A. Both leaks were not visible through visual inspection at the site. Oregon State plane coordinates appear at the image borders providing geo-referenced images of the regulatory mixing zone.

Two steps are necessary prior to rectifying the IR and video data to aerial photography. First, in the field, the cameras are focused such that the video camera’s field of view encompasses the IR camera’s field of view. This assures that the IR data fall within the spatial extent of the video imagery. Second, both cameras’ data are converted to JPEG format using the MixZon ZoneView post-processor.

Geo-referencing the JPEG-format data to the aerial photographs is done using a commercial off-the-shelf (COTS) mapping tool; ESRI’s ARCVIEW GIS along with the Spatial Analyst Extension and a basic ArcScript. The process starts with inputting the aerial photography and declaring the projection information (In our cases all the aerial photographs were referenced to the Oregon State Plane coordinate system using the North American Datum (NAD) 83/91 (HARN) in units of International feet). Next, the user imports the video captures into the GIS software. The video captures are essential for accurate referencing because they clearly show many features coincident between the aerial photograph and the study data.

Once the JPEG format video capture is imported to the GIS package, the Spatial Analyst’s Geo-referencing tool rectifies the JPEG to the aerial photo. Spatial statistics are tabulated via the Spatial Analyst to assure a highly-accurate fit between the video capture and the aerial photograph. Then, if the mixing zone extends beyond a single video image, an ArcScript will mosaic remaining images.

After the completion of the referencing of the video captures is complete the associated IR data are imported to the GIS software and referenced to the video captures. Again, spatial statistics are computed to assure a highly-accurate rectification.

Two methods of validation are then used to verify the accuracy of the rectification process. While in the field, we measure the dimensions of several objects that will appear in the video captures. Examples include downed logs, widths of stream channels or walking paths, and other objects of opportunity. These dimensions are measured against the dimensions of the objects in the video captures and if possible against the dimensions of the objects in the IR data. Second, we collect GPS information at specific locations easily recognizable in the video and IR data (for example, at topographic breaks along the shore/coastline) and compare it to the resulting rectified images.

3. Conclusions and Recommendations

We were able to successfully deploy our platform at an industrial discharge site near Portland, Oregon in August 2006. The results of two deployments are summarized in Figure 3. These figures are a mosaic of several images taken during each of the two deployments. The facility managers had also previously deployed buoys collecting thermistor temperature data in the mixing zone. The thermistor collected data is consistent and appears to be in good agreement with the aerial remote sensing images collected by our platform. Our platform was able to quickly detect leaks in the channel dyke that would be difficult or impossible to detect by thermistor probes. The data provided to regulators and plant managers was helpful in regulatory compliance assessment. In addition, the spatial thermal plume data provide a basis for hydrodynamic mixing zone model calibration and validation.

SBIR Phase II development will explore better methods for aiming and controlling the sensors, exploration of techniques for data collection and processing at oblique camera angles, and on the development of tools and data sets for mixing zone hydrodynamic simulation model development and validation.

In summary, we conclude that a balloon mounted remote sensing platform is technically feasible to remotely sense water quality at site scales. We were awarded an SBIR Phase II grant to continue development in May, 2006.

Acknowledgements

The authors would like to note the support provided by Ms. April Richards, Mr. Joel Salter, Mr. James Gentry, Ms. MaryLou Soscia, and Dr. James Gallup of USEPA.

References

1. USEPA, Water Quality Standards Handbook. 1984, USEPA: Washington, D.C.
2. DEQ, Oregon., Water Quality 2002 303(d) fact Sheet. 2002: Portland, OR.
3. Jirka, G.H., R.L. Doneker, and S.W. Hinton, User's Manual for CORMIX: A Hydrodynamic Mixing Zone Model and Decision Support System for Pollutant Discharges into Surface Waters. 1996, DeFrees Hydraulics Laboratory, Cornell University: Ithaca, NY.
4. Wu, C., Methodologies for Mixing Zone Model Validation of Surface Thermal Discharges in Large Rivers, in Department of Environmental Engineering. 2002, Oregon Graduate Institute, OHSU: Portland. p. 168.
5. Jensen, J.R., Introductory Digital Image Processing: A Remote Sensing Perspective. 1996, Upper Saddle River NJ: Prentice Hall.
6. Torgersen, C.E., et al., Multiscale Thermal Refugia and Stream Habitat Associations of Chinook Salmon in Northeastern Oregon. Ecological Applications, 1999. 9(1): p. 301-319.
7. Torgersen, C.E., et al., Airborne thermal remote sensing for water temperature assessment in rivers and streams. Remote Sensing of Environment, 2001. 76: p. 386-398.
8. FAA, FAR Section 101. 2005.
9. Akar, P.J. and G.H. Jirka, Hydrodynamic Classification of Multiport Diffuser Discharges. Journal of Hydraulic Engineering, 1991. 117(HY9): p. 1113-1128.

10. Davies, P.A., L.A. Mofor, and M.J. Neves, Comparisons of Remotely Sensed Observations with Modeling Predictions for the Behaviour of Wastewater Plumes from Coastal Discharges. International Journal of Remote Sensing, 1997. 18(9): p. 1987-2019.

11. Doneker, R.L. and G.H. Jirka, CORMIX1: An Expert System for Mixing Zone Analysis of Conventional and Toxic Single Port Aquatic Discharges. 1990, USEPA: Athens, GA.

12. Gawad, S.T., J.A. McCorquodale, and H. Gerges, Near-field Mixing at an Outfall. Canadian Journal of Civil Engineering, 1996. 23(1).

13. Fischer, H.B. and e. al., Mixing in Inland and Coastal Waters. 1979, New York: Academic Press.

14. Jirka, G.H. and R.L. Doneker, Hydrodynamic Classification of Submerged Single Port Discharges. Journal of Hydraulic Engineering, 1991. 117(6): p. 1095-1112.

15. Jirka, G.H.a.J.L., Waste Disposal in the Ocean, in Water Quality and its Control: Hydraulic Structures Design Manual, M. Hino, Editor. 1994, Balkema: Rotterdam.

16. Sedell, J.R., et al., Role of Refugia in Recovery from Disturbances: Modern Fragmented and Disconnected River Systems. Environmental Management, 1990. 14: p. 711-724.

17. Valeo, C., H. Shen, and I.K. Tsanis, Modeling Mimico Creek as a Surface Discharge. Journal of Hydraulic Research, 1996. 24(1).

18. Valeo, C. and I.K. Tsanis, Two Case Studies of Dilution Models applied to Thermal Discharges. Canadian Journal of Civil Engineering, 1996. 23.

19. Yotsukura, N. and W.W. Sayre, Transverse Mixing in Natural Channels. Water Resources Research, 1976. 12: p. 695-704.

20. Tsanis, I.K., C. Valeo, and Y. Diao, Comparison of Near-Field Mixing Models for Multiport Diffusers in the Great Lakes. Canadian Journal of Civil Engineering, 1994. 21.

21. Rawn, A.M., F.R. Bowerman, and N.H. Brooks, Diffusers for Disposal of Sewerage in Seawater. J. Sanitary Engineering Division, ASCE, 1960. 86: p. 65-105.

22. Campbell, C.W. and A.G. Keith. Karst Groundwater Hydrologic Analysis Based on Aerial Thermography. in 2000 Annual Meeting and International Conference of the American Institute of Hydrology. 2000. Abstracts: Atmospheric, Surface and Subsurface Hydrology and Interactions.

23. Doneker, R.L., J.D. Nash, and G.H. Jirka, Pollutant Transport and Mixing Zone Simulation of Sediment Density Currents. Journal Hydraulic Engineering, 2004. 30(4): p. 349-359.

24. Baumgartner, D.J., W.E. Frick, and P.J. Roberts, Dilution Models for Effluent Discharges (3rd Ed.). 1994, USEPA: Newport, OR.

25. Davis, L.R., Fundamentals of Environmental Discharge Modeling. CRC Mechanical Engineering Series. 1999, Boca Raton: CRC Press. 165.