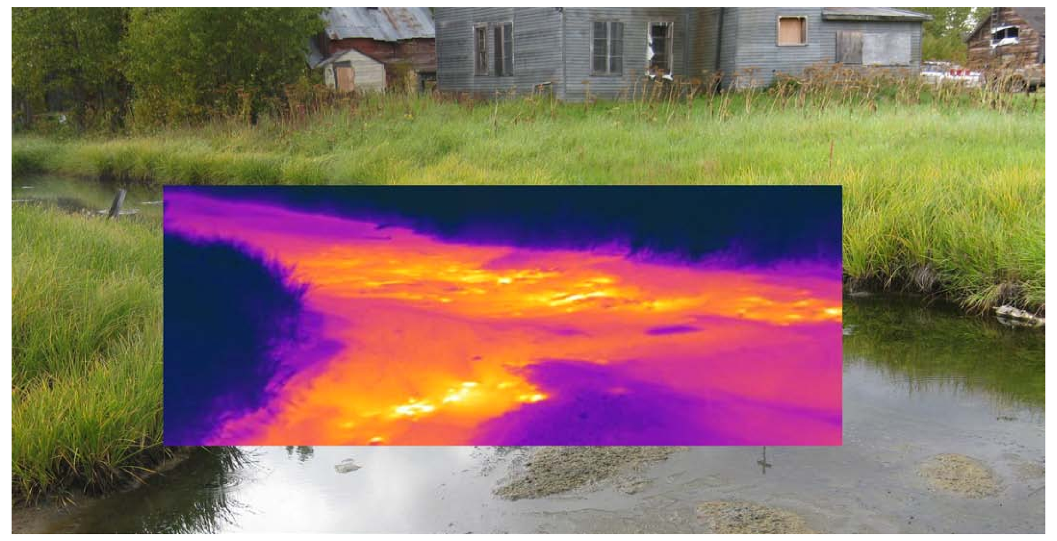


Use of Airborne Thermal Imaging to Quantify Heat Flux and Flow Rate of Surface Geothermal Fluids at Pilgrim Hot Springs, Alaska

Christian Haselwimmer* **and Anupma Prakash**

Earth and Planetary Remote Sensing Group, Geophysical Institute, University of Alaska Fairbanks. *Corresponding author: chha@gi.alaska.edu

AGU FALL MEETING 2011 San Francisco, California, USA | 5-9 December

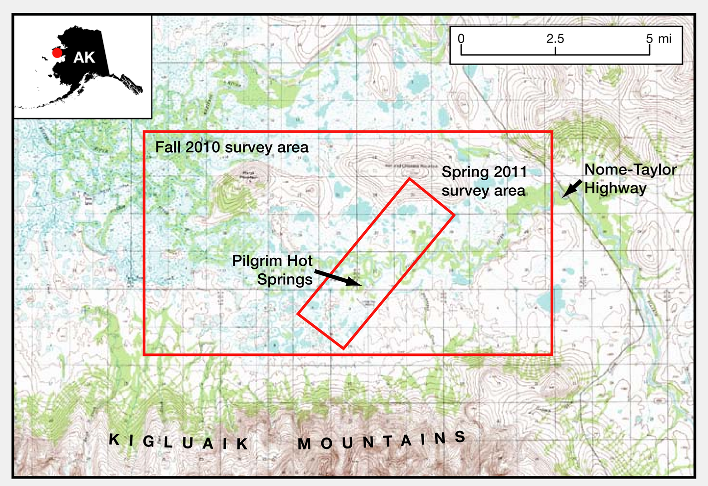
H51C-1223

1. Introduction

Hot springs represent one component of convective heat loss from hydrothermal systems. Quantifying this heat flux is important for monitoring of geothermal systems [1] as well as within surface heat flow studies for geothermal resource assessment [2]. Conventionally the heat flux supporting hot springs is determined using direct measurements of temperature and outflow rate [1] or with geochemical approaches such as the chloride flux method [3]. These techniques may be time consuming or yield innaccurate results when the source or outflow of geothermal fluids is poorly defined. We present an approach to quantifying the heat flux and flow rate of hot springs based upon analysis of airborne thermal imagery.

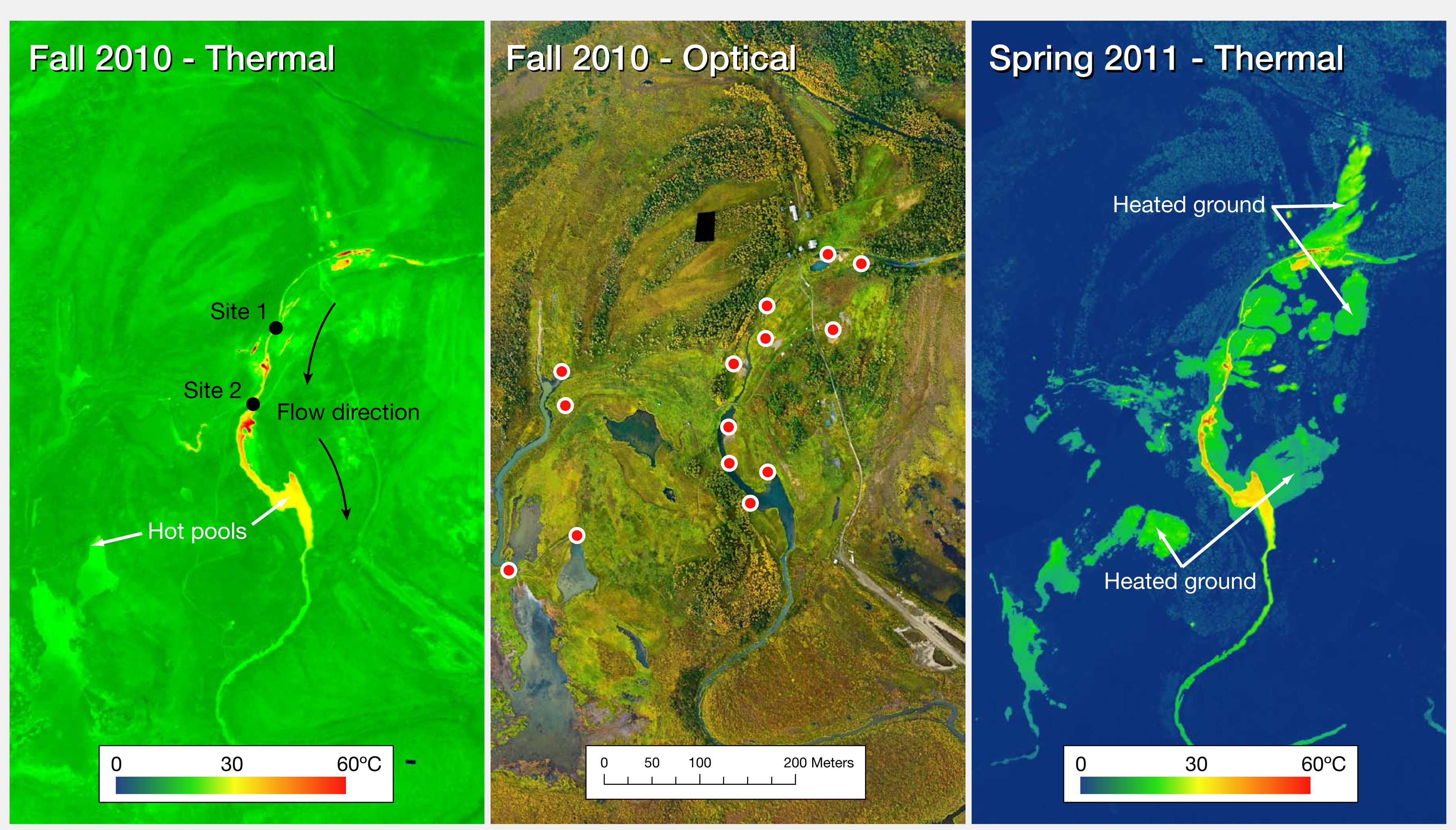
2. Study Area: Pilgrim Hot Springs, AK

- Low to moderate temperature geothermal system located ~75km NE of Nome on Seward Peninsula
- Shallow 90°C aquifer fed from deeper reservoirs of at least ~110-150°C [4]
- Phase 1 of DOE/AEA funded project using satellite and airborne remote sensing for geothermal exploration and resource assessment



3. Airborne Remote Sensing

Airborne thermal infrared (Forward Looking Infrared Radiometer / FLIR - 1.2m) and optical (20cm) images acquired on two surveys in September 2010, and April 2011 [5]. Pre-processing involved registration and mosaicking of images and calibration of thermal data to surface temperature using in-situ measurements of atmospheric parameters and ground temperatures.

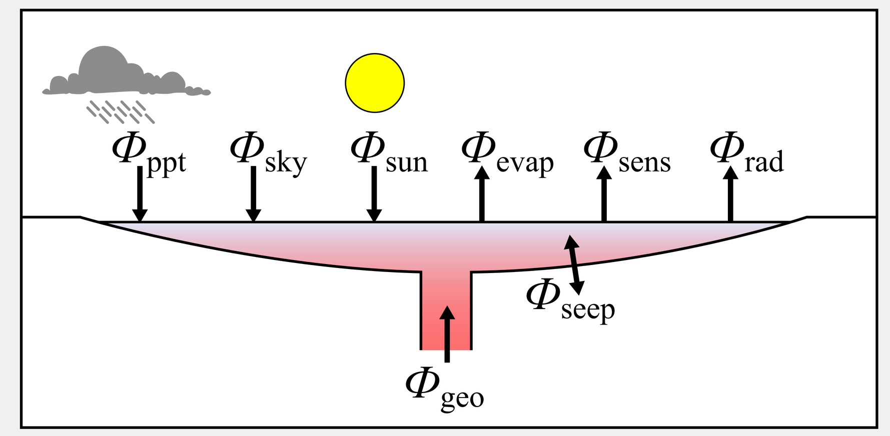


Hot springs (red dots) and pools are outlined by elevated surface temperatures in thermal data. Heated ground is indicated by areas of anomalous snow melt in Spring 2011 data.

4. Heat Budget Model for Surface Geothermal Fluids

Simplified heat budget model adapted from [6,7] used to calculate heat flux maintaining surface geothermal pools. The total heat budget for a water body (in Watts) expressed as:

$$\Phi_{total} = \Phi_{geo} + \Phi_{ppt} + \Phi_{seep} + \Phi_{evap} + \Phi_{sens} + \Phi_{rad} + \Phi_{sun} + \Phi_{sky}$$



- Φ_{geo} = heat input from geothermal fluids
- Φ_{ppt} = heat input from precipitation
- Φ_{seep} = heat flux from seepage
- Φ_{evap} = heat loss from evaporation
- Φ_{sens} = heat loss via sensible heat transfer
- Φ_{rad} = heat loss by radiation
- Φ_{sun} = heat input from solar radiation
- Φ_{sky} = heat input from atmospheric radiation

Simplified model removes Φ_{ppt} and Φ_{seep} as heat fluxes are small. The temperature of surface non-geothermal waters is used to account for Φ_{sun} and Φ_{sky} terms. Within FLIR surface temperature data geothermal pools are located and the geothermal heat flux density (q in W/m^2) is calculated on a pixel by pixel basis using:

$$q_{geo} = (q_{rad} + q_{evap} + q_{sens}) - (q_{radAmb} + q_{evapAmb} + q_{sensAmb})$$

Where q_{rad}, q_{evap}, q_{sens} and q_{radAmb}, $q_{evapAmb}$, $q_{sensAmb}$ are radiative, evaporative and sensible heat fluxes for each pixel and at the ambient temperature of non-geothermal waters calculated using:

Radiative heat fluxes calculated with Stefan-Boltzmann equation:

$$q_{rad} = \varepsilon \sigma T^4$$

Where σ = 5.67 x 10^{-8} (Stefan-Boltzmann constant in W/m^2 K^{-4}); ε = water emissivity (0.98); T = water temperature (°C)

Evaporative and sensible heat fluxes calculated using formula of [8]:

$$q_{evap+sens} = [\lambda(T_{sv}-T_{av})^{1/3} + b_o W_2][e_s - e_2 + C(T_s - T_a)]$$

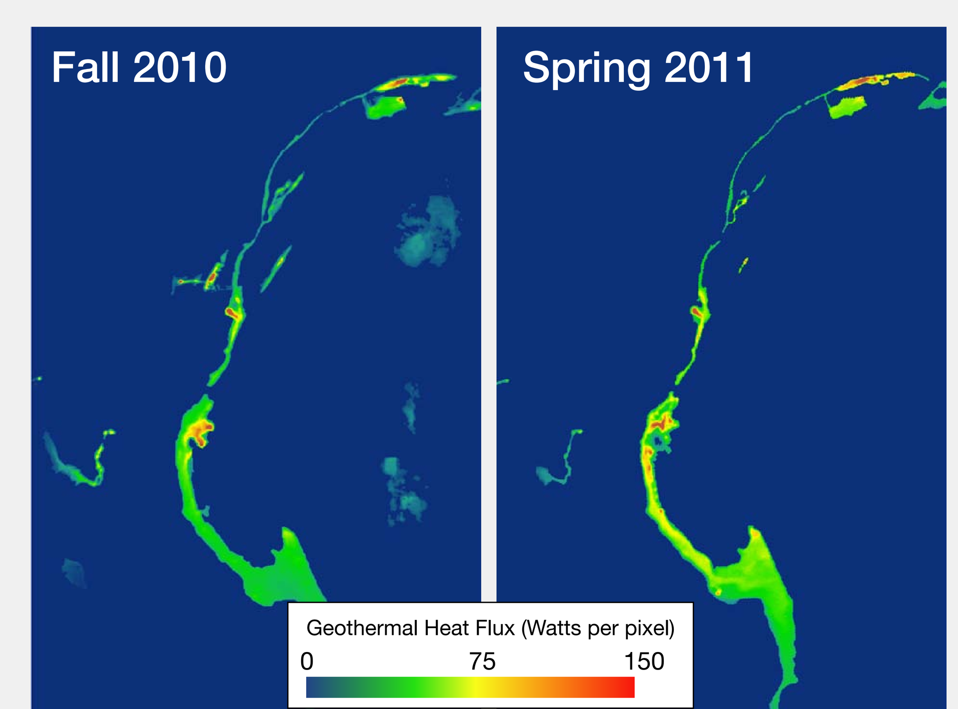
Where λ = 2.7 (constant); b_o = 3.2 (constant); W_2 = wind speed at 2m height (m/s); e_s = vapor pressure of water at T_s (mbar); e_2 = vapor pressure of water at 2m height (mbar); C = 0.61 (constant); T_s = water surface temperature (°C); T_a = air temperature (°C); T_{sv} = virtual water surface temperature (°C); T_{av} = virtual air temperature (°C)

Model applied to FLIR data acquired during Fall 2010 and Spring 2011 surveys. Total heat flux is sum of heat fluxes for each pixel.

Assuming a fixed hot spring (81°C) and ambient water temperature the flow rate (V in m^3/s) was calculated from the total geothermal heat flux (Φ_{geo}) using:

$$V = [\Phi_{geo} / (h_s - h_{amb})] / \rho_w$$

Where h_s = enthalpy of hot spring water; h_{amb} = enthalpy of water at ambient temperature; ρ_w = density of water (kg/m^3)

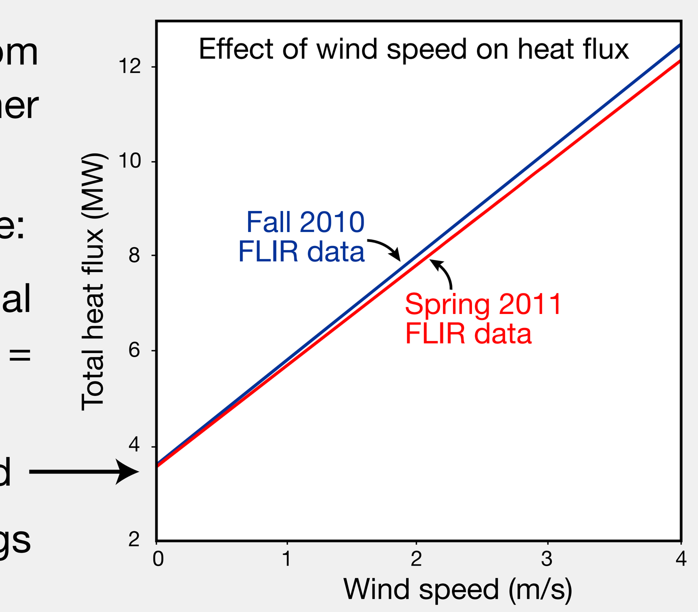


5. Results and Validation

Summary of hot spring heat flux/flow rate estimates from airborne FLIR data and in-situ measurements (refer to Section 3 of this poster for site locations):

Source of estimate	Total heat flux	Flow rate	Notes
Airborne FLIR - Fall 2010	**3.62 MW**	**0.43 feet^3/s**	Conservative estimate assuming wind = 0
Airborne FLIR - Spring 2011	**3.67 MW**	**0.44 feet^3/s**	Conservative estimate assuming wind = 0
1979 flow rate measurement [9]	2.00 MW	0.15 feet^3/s	Hot stream gauged at Site 1 (See panel 3)
1983 flow rate measurement [10]	-	0.20 - 0.50 feet^3/s	Hot stream gauged at Site 1
08/2011 flow rate measurement	-	0.39 feet^3/s	Hot stream gauged at Site 2

- Conservative estimates of heat flux / flow rate from airborne FLIR (wind speed = 0 m/s) are generally higher than in-situ observations
- BUT true heat flux is likely to be higher than this estimate:
  - > Wind speed of 0 m/s is unrealistic: average annual wind speed at nearest met station (K2 ~50km NE) = 3.18 m/s from [11]
  - > Heat flux estimates are very sensitive to wind speed
  - > In-situ measurements of flow rate of hot springs probably underestimate total outflow
- With more plausible wind speeds (0.5 - 1.5 m/s) heat flux estimates from FLIR range from ~ **4.74 - 6.96 MW** that corresponds to flow rates of ~ **0.61 - 0.90 feet^3/s**



6. Summary

- The convective heat flux supporting surface geothermal fluids and associated flow rate can be estimated using a heat budget model applied to airborne thermal imagery
- Using this approach at Pilgrim Hot Springs has provided conservative estimates of the surface convective heat flux that are higher than previous field-based approaches
- Airborne thermal imaging provides a rapid, repeatable method with synoptic coverage for estimation of hot spring heat flux and flow rate

Acknowledgements

This research is funded by the Department of Energy Geothermal Technologies Programme (CID: DE-EE0002846) and the Alaska Energy Authority Renewable Energy Fund Round III (project PI: Gwen Holdmann, Alaska Center for Energy and Power). We thank Jessie Cherry, Forest Kirst, Matt Nolan, Markus Mager, Kate Schaefer, and Peter Illig for providing support for airborne remote sensing and field data acquisition.

References

1. Heasler, H.P., Jaworowski, C., and Foley, D. (2009) Geothermal systems and monitoring hydrothermal features, in Young, R., and Norby, L., eds., Geological Monitoring: Boulder, Colorado, Geological Society of America, p. 105–140, doi: 10.1130/2009.monitoring(05).
2. Wisian, K.W., Blackwell, D.D., and Richards, M. (2001) Correlation of Surface Heat Loss and Total Energy Production for Geothermal Systems. Geothermal Resources Council Transactions, Vol. 25, August 26-29, 2001.
3. Ellis, A.J., and Wilson, S.H. (1955) The heat from the Wairakei-Taupo thermal region calculated from chloride output. New Zealand Journal of Science and Technology, B36, 622-631.
4. Liss, S.A. and Motyka, R.J. (1994) Pilgrim Springs KGRA, Seward Peninsula, Alaska: Assessment of fluid geochemistry. Geothermal Resources Council Transactions, Vol. 18.
5. Haselwimmer, C.E., Prakash, A., and Holdmann, G. (2011) Geothermal Exploration at Pilgrim Hot Springs, Alaska Using Airborne Thermal Infrared Remote Sensing. Geothermal Resources Council Transactions, Vol. 35, October 23-26, 2011.
6. Oppenheimer, C. (1996). Crater lake heat losses estimated by remote sensing. Geophys. Res. Lett., 23(14):1793–1796.
7. Patrick, M., Dean, K., and Dehn, J. (2004). Active mud volcanism observed with landsat 7 ETM+. Journal of Volcanology and Geothermal Research, 131(3-4):307-320.
8. Ryan, P. J., Harleman, D. R. F., and Stolzenbach, K. D. (1974). Surface heat loss from cooling ponds. Water Resour. Res., 10(5):930–938.
9. Harrison, W. and Hawkins, D. (1979). Water and heat flow measurements and their relationship to power estimates at pilgrim springs, alaska. Technical report, University of Alaska, Geophysical Institute.
10. Woodward-Clyde Consultants (1983). Geothermal energy development at Pilgrim Hot Springs, Alaska, Phase II: Results of drilling, testing, and resource confirmation. Technical Report by Woodward-Clyde Consultants.
11. Seward Peninsula Hydrometeorology Network: http://ine.uaf.edu/werc/projects/seward/index.html