OLYMPEX
Ground Validation Experiment
Field Operations Plan
(Version 3)

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Preamble

This document is a comprehensive summary of the field plans, objectives and instrumentation to be deployed for OLYMPEX, as understood at the time of this writing. The objectives will be achieved by means of coordinated ground instruments for snow and rain, rawinsonde serial ascents, ground-based radar, aircraft with radars and passive microwave instruments to simulate the GPM satellite measurements, and airborne microphysical sampling. Measurements will be made over the ocean, on the windward side of the Olympic Mountains, over the snowfield in the high terrain, and on the leeside of the mountain range. An Operations Center at the University of Washington will be the base where all the components of the project will be coordinated day-to-day during the field operations.

1. General background of the OLYMPEX ground validation campaign for GPM

1.1 Ground validation goals for midlatitude precipitation

The primary objective of the Global Precipitation Mission (GPM) is to measure rain and snow globally especially in areas lacking surface observations or ground-based radar coverage. In order to achieve this goal, the GPM constellation of satellites must be able to detect solid and liquid precipitation over a wide range of intensities (from 0.2 mm hr^{-1} to 110 mm hr^{-1}), a wide range of locations (from ocean to complex terrain), and a wide range of regimes (light snowfall to intense convection). The core satellite of GPM was launched on 27 February 2014 and is instrumented with the GPM Microwave Imager (GMI) and the Ku/Ka band Dual Frequency Precipitation Radar (DPR). To satisfy the GPM measurement requirements and to assess how remotely sensed measurements of precipitation can be applied to a range of data applications (e.g. determining storm structures, monitoring flooding events and droughts) ground validation (GV) field campaigns are vital. We describe herein the Operations Plan for the comprehensive ground validation Olympic Mountain Experiment (OLYMPEX) for GPM to be conducted in Washington State during November 2015 – February 2016. This experiment will address a wide range of GV needs.

The Olympic Peninsula is an ideal location to conduct a GV campaign for GPM. It is situated within an active midlatitude winter storm track in the northwest corner of Washington State. It reliably receives among the highest annual precipitation amounts in North America ranging from over 2500 mm on the coast to about 4000 mm in the mountainous interior. In one compact area, the Olympic peninsula ranges from ocean to coast to land to mountains, where the terrain height ranges from sea-level to elevations over 2000 m over a distance of approximately 50 km. This unique venue is of an ideal size for a field campaign involving aircraft, radars, and other ground-based sensors. OLYMPEX will be able to monitor the storm characteristics and processes over the ocean, their modification over complex terrain, and the resulting hydrologic impacts. OLYMPEX is ideally suited to quantify the accuracy and sources of variability and uncertainty inherent to GPM measurements in such a varied region of the midlatitudes.

OLYMPEX simultaneously addresses several basic GPM goals:

- Physical validation of the precipitation (rain and snow) algorithms for both the GMI and DPR.

- Assessing GPM precipitation uncertainty in midlatitude frontal systems as a function of space and time scales, physical and dynamical mechanisms, precipitation intensity, storm structure, and underlying terrain.
- Quantifying the accuracy and uncertainty of the GPM precipitation data and its hydrologic applicability.
- Merging numerical modeling and satellite observations to optimize precipitation estimation in hybrid monitoring systems of the future.

Through a combination of surface-based instrumentation, snowpack monitoring strategies, multi-frequency radars, aircraft satellite simulators, aircraft and surface-based microphysical measurements, hydrologic measurements, and numerical model estimates, OLYMPEX will provide a comprehensive picture of the surface and in-cloud microphysical properties and their variability for a wide-range of meteorological and topographic conditions. The following sections will provide details of the Operations Plan for the OLYMPEX project.

1.2 Location and dates of the field project

OLYMPEX will take place on the Olympic Peninsula, the northwest corner of Washington State, as shown in Figure 1. Due to the mean southwesterly flow and frequent passage of midlatitude cyclones, the region is characterized by a wetter, windward side on the southern and southwestern side of the Olympic Mountains and a drier, leeward side located to the north and northeast of the Olympic Mountains. A majority of the focus of the campaign will be on the wetter southwest side with radars and ground instrumentation placed to sample storms as they approach from the Pacific Ocean and are then modified as they traverse across the higher terrain. Two river basins will be the focus of the campaign, the Quinault River and the Chehalis (shown in Figure 2). The Quinault has headwaters in the high terrain of the Olympic Mountains and flows almost due westward towards the Pacific Ocean. The Chehalis has an upper branch, which originates in the higher terrain on the south side of the Olympics, and a lower branch located in southwestern Washington state to the south of the Olympics.

OLYMPEX will occur from fall 2015 through winter 2016. Different observational networks will have different time periods of operation. The ground instrumentation will be installed in the early fall 2015 (by September for the higher elevation locations and by mid-October for the lower elevation locations) and will remain onsite until spring 2016. Precipitation and flooding of river basins in the Pacific Northwest is most frequent during mid-November through January. The radars will operate from November 10 through 22 December 2015. There will be a two-week break for the holidays, and then the radars will resume operations from 3–15 January. The aircraft will operate for a 6-week period, 10 November–21 December 2015.

1.3 Collaborative agencies in the Pacific Northwest

The land areas over which OLYMPEX will take place are on the Olympic Peninsula where large portions of the land are administered by the National Park Service (NPS), the US Forest Service (USFS), and the Quinault Nation (Figure 3).

<u>National Park Service</u>

The Olympic National Park covers most of the Peninsula, encompassing the high terrain and some sections of the Washington Coast. Consequently, much of the interior of the Peninsula is remote, and access is limited to trails and unpaved roads that are closed in the winter. Any ground instrumentation that is placed in the Park will require special permits to insure that the installation, maintenance and operation of the instruments comply with the Wilderness Act of 1964 and have a minimum impact on the natural ecosystem. In addition, access to instruments installed at the high terrain may require 2-day hike on foot in winter conditions.

U. S. Forest Service

The USFS has jurisdiction over many areas immediately surrounding the Park, with some of these regions designated as Wilderness Areas. Any ground instruments installed within Forest Service land also require permits and access to the instruments will vary depending on the location. Some regions are quite remote with limited access by unmaintained roads. Other roads are gated in the winter for wildlife protection and require a special permitting process to obtain permission to make installations during the winter season.

Quinault Indian Nation

The Quinault Indian Nation (QIN) reservation covers a significant portion of the coastal and southwestern side of the Olympics, including the lower portion of the Quinault River. Much of the area is also remote with limited access via unpaved roads. Any instrumentation installed within the Reservation boundaries requires permits from the QIN. We have developed a working relationship with the QIN Department of Natural Resources and they have been very supportive of the OLYMPEX project and are working closely with us to insure its success. Most importantly the QIN will host the NPOL and D3R radars (see Section 6.1 below).

1.4 Partner projects

RADEX

An important partner within NASA is the RADEX (Radar Definition Experiment), which will make radar and passive microwave measurements with the ER-2 aircraft in coordination with the OLYMPEX DC-8 and Citation aircraft (see Section 7 below). The goal of RADEX is to obtain information that will advance the development of radars to monitor clouds from space, including where cloud processes are active in thin clouds and a wide range of ambient temperatures. These goals lead to the desire for the same type of measurements that are sought in OLYMPEX, so OLYMPEX and RADEX will work very well in a joint experiment.

Environment Canada

Environment Canada and NASA have a rich history of collaborating on ground validation activities in support of space-based missions. There is an existing collaborative agreement between the organizations to cover this type of activity (prior such programs being the Canadian CloudSat CALIPSO Validation Experiment in the winter of 2006/07 and the GPM Cold Season Precipitation Experiment in 2011/12). The Environment Canada contribution to OLYMPEX will be to support the validation of GPM products in complex terrain by monitoring the precipitation processes occurring on the leeside of the Olympic Mountains. Operating on the southern tip of Vancouver Island, BC, they will provide rawinsonde ascents and radar measurements that will document leeside processes. The radar measurements will extend over the NASA instrumentation located on the leeside of the Olympic range, and the radar and rawinsonde data will be an ideal complement to similar measurements made by NASA and NSF facilities on the windward side of the Olympic Mountains. Environment Canada's participation also supports goals related to modeling and data assimilation studies in the Meteorological Research Division that use the West Coast (centered on Georgia Strait) version of High-Resolution Ensemble Kalman Filter (HREnKF) Forecasting system.

NSF/DOW

The National Science Foundation (NSF) is supporting a University of Washington grant under which a Doppler on Wheels (DOW) radar will be deployed during OLYMPEX. The objective being pursued under this DOW deployment is determination of the dynamical and microphysical processes leading to rapid growth and fallout of precipitation on the windward sides of mountain ranges. Obtaining these measurements in the context of the GPM ground validation measurements is seen as an opportunity for the NSF project to pursue its objectives. At the same time the DOW measurements will supplement the NASA NPOL radar measurements (see Section 6) by obtaining dual-polarimetric data in the Quinault Valley below the beam of the NPOL radar.

2. Overview of Expected Weather during OLYMPEX

2.1 Expected storm tracks and typical upper level patterns

From October through May, frequent midlatitude cyclones and their frontal systems make landfall on the Olympic Peninsula from the west and southwest. The upper-level flow patterns associated with the frontal systems vary on timescales of days to weeks. Cluster analysis on 5-day averaged 500 hPa heights shows that the upper-level flow can be segregated into four regimes (Casola and Wallace 2007). In Figure 4, these patterns are shown and can be distinguished from one another by the location and amplitude of their respective ridges and troughs. The offshore trough (OT) has a ridge near the Bering Sea and a trough to the west of the North American west coast. The Alaskan ridge (AR) exhibits a high amplitude ridge centered in the Gulf of Alaska and northwesterly flow along the North American west coast. The coastal ridge (CR) has a ridge aligned with the North American west coast and the Rockies ridge (RR) exhibits a low-amplitude ridge along the Rocky Mountains with nearly zonal flow across the Pacific. The OT and RR patterns are associated with westerly or southwesterly flow and tracks of frontal systems impinging on the Pacific Northwest. They are also most often associated with high precipitation events in the Pacific Northwest. The RR pattern is the most common pattern during the fall and winter months. The AR pattern is associated with more northwesterly flow that can either be dry or associated with colder frontal systems. The CR pattern is a more quiescent pattern associated with a general lack of frontal passages and blocking of the mean westerlies. The AR and CR patterns are relatively infrequent but can at times interrupt the more normally rainy regimes.

The mean surface flow for the period November through March is southwesterly (Figure 5). This allows moisture-laden air from the Pacific to directly impinge on the Olympic Peninsula contributing to large annual precipitation totals. The air is further lifted over the Olympic Mountains enhancing the production of precipitation. Subsequently, the annual precipitation amounts range from 2500 mm on the coast to more than 4000 mm in the mountainous interior.

2.2 Frontal system sectors

The Pacific frontal systems passing over the Olympic Peninsula typically have three sectors, each with different environmental characteristics, cloud patterns, and precipitation characteristics. These sectors illustrated conceptually in Figure 6 are labeled as prefrontal, frontal and postfrontal.

Prefrontal sector

The prefrontal sector is located to the east and north of an occluded front or cold front and north of a warm front (if present). It is characterized by warm advection, rising melting level, and broad stratiform clouds with steady rainfall. The rain can either be light and drizzly or steady and heavy depending on the moisture content and the degree of synoptic- and meso-scale forcing.

Frontal Sector

The frontal sector is a broad, quasi-linear cloud shield within which a cold (or occluded) front and its associated frontal circulations contribute to the production of precipitation. It is characterized by a broad precipitating region called the wide-cold frontal rainband, and embedded within this rainband, there is a narrow region of high rainrates called the narrow-cold frontal rainband. The environmental characteristics can change rapidly with the passage of the front. For example, the melting level can drop in elevation sharply with frontal passage.

Postfrontal Sector

The postfrontal sector is situated behind (west) of the cold (or occluded) front and is characterized by cold advection, lowering melting level, conditional instability, and a field of small-scale convective clouds separated by clear air. The upper level trough and vorticity center is often co-located with this sector. Due to the deep cold advection over the relatively warmer oceanic water, the small convective clouds sometimes arrange themselves in hexagonal patterns labeled as open-celled convection. When postfrontal convective elements pass over land and are lifted over higher elevations, they often grow in scale and produce significant precipitation and snowfall over the higher terrain. The precipitation in this sector is showery in nature and can contribute significantly to the total rain and snowfall produced by the entire storm system.

3. Observational objectives and experimental strategy

An attractive feature of the Olympic Peninsula is that it offers the opportunity to test several observational challenges of GPM in midlatitude frontal systems over both ocean and adjacent complex terrain. The ability to observe such cloud systems is the primary difference between the Tropical Rainfall Measuring Mission (TRMM) and GPM. In the tropical latitudes surveyed by TRMM, the temperature gradient is weak and precipitation detection algorithms are consequently simplified, snow measurement is not required, and stratiform precipitation is a by-product of convection. In midlatitudes, horizontal temperature gradients are strong, snow measurement is required, and stratiform precipitation is produce by frontogenetical lifting rather than convective processes. In addition, detection of frontal precipitation from space is further complicated by two factors: convection is embedded in frontal clouds, and frontal precipitation is highly modified where it is passing over complex terrain. Finally, assessment of runoff and snowpack in midlatitudes by GPM is highly dependent on the ability of the satellite to detect frontal snow and rain over complex terrain. OLYMPEX is designed to address all of these aspects of midlatitude frontal rain in ways that will aid understanding of how GPM is able to produce useful data in regions of midlatitude frontal precipitation. The observational objectives of OLYMPEX may be summarized by seeking answers to the following questions:

- How do microphysical and dynamical processes determine particle size distribution in rain and snow and how do they vary in the vertical over a wide range of temperatures with emphasis on variations of the processes across the melting layer?
- How do the microphysical and dynamical processes change as storms move from ocean to coast to land to windward side to high terrain to leeside of mountains?
- How do the microphysical and dynamical processes vary between prefrontal, frontal, and postfrontal storm sectors?
- Can GPM determine the buildup and melt-off of high-terrain snowpack over the full winter season?
- Can GPM determine the hydrologic response to storm passages?

To achieve answers to the above questions representing OLYMPEX objectives, the field program will consist of a strategy of coordinating a variety of ground-based and aircraft measurements. Figure 1 shows the locations of the ground-based instrumentation. Aircraft flights will supplement this network with measurements over the ocean, radars and ground instruments.

Serial rawinsonde ascents at 3-h intervals on the windward and lee sides of the Olympic range will provide the ambient temperature, moisture, and wind profiles, which undergo significant variation during the passage of storms and provide the essential context for making deductions about the microphysical and dynamical processes contributing to the frontal precipitation. Soundings upstream over the ocean will be provided by dropsondes from the DC-8 aircraft.

Surface rain measurements in the Quinault Valley will document how the rainfall and its drop size distribution vary from the coast inland and into the mountains. The radars will determine the vertical distributions of hydrometeors and associated cross-barrier winds as storms pass over the network. Aircraft will provide GPM proxy measurements with downward-looking radars and passive microwave sensors and in situ microphysical sampling within the context of all of the ground-based and airborne radar and radiometer measurements. These observational components of OLYMPEX will be supplemented by real-time regional modeling using the UW WRF ensemble.

4. Deployment of instrumentation for rain and snow measurements and in situ particle sampling at the ground

The existing surface network on the Olympic Peninsula consists of few Automated Surface Observing Systems (ASOS) stations, a Climate Reference Network (CRN) station, several Cooperative Observing (COOP) sites, Remote Automated Weather Station (RAWS) sites and four SNOTEL (SNOpack TELemetry) sites. With the exception of the SNOTEL sites, these observations are limited to coastal and lowland locations that surround the Olympic Mountains (see Figure 7). In order to document how the microphysical and dynamical processes change as storms move from ocean to land to high terrain, these observations will be supplemented with a variety of ground-based microphysical and precipitation gauge instruments in critical areas. The Quinault River basin is a narrow southwest-northeast oriented watershed on the windward side of the Olympic Mountains (Figure 2). As such it is ideally suited for concentrated radar and ground measurements. Rain gauges and disdrometers will be distributed along the valley, radar coverage will be intensified there with six radars, rain gauges, and a supplemental snow observation strategy will be implemented to observe the buildup and melt-off of the snowpack at higher elevations. In order to improve the quantitative assessment of rainfall in the Chehalis River basin (Figure 2) and the hydrological response, an enhanced rain gauge network will be implemented throughout the Chehalis basin.

4.1 Quinault Area Instrumentation

Figure 8 shows the names and locations of OLYMPEX special ground instrumentation sites on the windward side of the Olympics. These sites are arranged to observe precipitation characteristics along the Quinault River Valley at various distances from the NPOL radar. These instrument sites will help document the variation of precipitation characteristics as a function of distance from the coastline and crest of the mountain range on the windward side of the Olympic range.

Table 1 lists the instruments that will be installed at each site. Note that the types of instruments at each site are determined by the availability of power, wireless signal strength, and accessibility. Sites such as Wallace Cabin, Fish Hatchery, and CRN are all lowland (elevations < 300 ft) sites with power and easy road access, so that a more complete set of instruments is possible and can include MRR, 2DVD, and Parsivel. Other lowland sites without power, such as the Seed Orchard, Bunch Field and Graves Creek campground can only have limited instrumentation such as tipping bucket rain gauges and a Parsivel and/or Pluvio supported with a battery and solar panel set up. Since these lowland sites are relatively accessible, batteries can be exchanged during regular checks. Therefore, only 1-2 deep-cycle batteries should be necessary at these sites.

There will be three high-elevation sites in the Quinault region. Neilton Point, at 2156 ft located on the southern ridge of the Quinault River, is within the rain/snow transition zone, i.e. where falling precipitation can be either rain or snow depending on the environmental temperature and the sector of the storm. This zone is not routinely observed in the Olympic Mountains and OLYMPEX, and instruments at this site will provide a rare opportunity to document the critical processes that occur within this zone. Neilton Point has power so that it will be possible to install a full suite of microphysical instruments including MRR, PIP, Hot Plate and Parsivel. The site is accessible by unpaved road that will require a 4WD vehicle (with chains) in winter. Therefore, access for maintenance may be somewhat limited during cold storm events.

The other two high-elevation sites, Upper Quinault and Wynoochee, are very remote and in wilderness areas. The Upper Quinault site is within the National Park and is only accessible on foot via a 13 mile trail, some of which could be snow-covered. At 2033 ft, it too will be within the rain/snow transition zone. At this location, a remote APU (Pluvio and Parsivel) can be installed provided they are powered with a bank of 8 deep-cycle batteries and a solar panel. Initial tests of this type of set up have shown that the batteries can operate for a long period of time (2–4 weeks) without recharging as long as there are a few intermittent sunny periods for the solar panel to operate. The Upper Quinault installation will require a special permission from the Park Service and that process is underway.

The high elevation site Wynoochee Trailer is within a National Forest Service designated Wilderness Area, for which the road is only open from beginning of May through end of September. We plan to install an instrumented trailer (see Figure 9) about 9 miles inside the Wilderness Area boundary along FS Road 2270 at an open area just off the road. The instrument and battery set-up will be the same as at Upper Quinault. Since this site is at 3160 ft, there will be considerable snow during the winter and frequent maintenance may be required to dig out the trailer and instruments. During the winter, the road is gated and motor vehicle access is restricted. With permission from the Forest Service, we should be able to access the site with a vehicle up to the elevation of the snow pack, but then will need to hike (or possibly use a snowmobile) the rest of the way.

4.2 High Terrain Network and Snowpack Monitoring

As noted above, some instrumentation exists at higher elevations designed to monitor weather conditions, snow water equivalent of falling precipitation (either rain or snow) and snow pack accumulation. These stations are all at high elevations (~5000 ft) and include the four SNOTEL sites and the Northwest Avalanche Center (NWAC) site at Hurricane Ridge (see Figure 10). These are all long-term, permanent installations designed to support short-term weather forecasts for storms and avalanches and long-term trends in water supply.

In order to document microphysical properties at high elevations, a suite of instruments is installed at Hurricane Ridge near the NWAC site. Power is available at this site. The instruments are located on top of a generator house and include a PIP, MRR, Parsivel and Hotplate (see Figure 11). This installation coordinates with the observations made by the Environment Canada X-band radar located 50 miles north at Rocky Point on Vancouver Island. The Hurricane Ridge installation and the other three higher elevation sites within the Quinault area described above will document the variability of microphysical processes within and above the rain/snow transition zone.

The four SNOTEL sites and one NWAC site are insufficient to fully describe the accumulation of snow at all elevations over the Olympic Mountains. In order to gain additional information on the snow depth and its variability, a suite of remote cameras has been installed at 18 locations within the general area indicated in Figure 10. The cameras were installed during the late summer of 2014. Each camera is placed to take hourly pictures of a marked snow stake. Small remote temperature sensors are also placed near the snow cameras. The cameras and temperature sensors are left onsite throughout the winter and collected the following summer. The locations have been chosen to be close to historical snow course locations where snow depth measurements were made through the early 1970s and the locations are shown in Figure 12. Initial results from prior snow camera installations at the SNOTEL sites have shown this method to be an accurate and cost-effective way to determine snow depth. Snow water equivalent (SWE) estimates from the snow depth measurement require an estimate of snow density and research is ongoing to determine the best method to estimate density.

In addition to these measurements, the National Park Service performs snow surveys performed by observers flown in by helicopter, which will supplement the other snow measurements. It is possible that additional snow surveys could be made during OLYMPEX, funding permitting.

4.3 Tipping Bucket Rain gauge Networks

Quinault

The UW has installed a network of tipping bucket gauges that transect the ridge between the Quinault and Queets Rivers and includes two gauges along the coast (see Figure 13). This network has been deployed since ~2005 (Minder et al. 2008) and will be deployed up to and including the OLYMPEX time frame. These data are recorded in data loggers, which are retrieved manually at the end of the winter season. The data from some of the lower elevation gauges can be downloaded midseason, but the higher elevation gauges are usually inaccessible during the winter due to snow on the roads.

There will be approximately 20 additional dual-tipping bucket gauges available for OLYMPEX, 10 of which will be installed within the Quinault. These gauges can be monitored in real time provided there is sufficient cellphone coverage (which is not always available in the Quinault region). These gauges will be installed at the locations listed in Table 1 (i.e. at the Seed Orchard, Graves Creek, etc.). The remainder of the gauges could be installed at additional locations of opportunity along the Quinault River transect, be used to expand rainfall estimates along the coast, provide additional rainfall estimates on the north side of the Olympics at elevations lower than Hurricane Ridge, or in the lowlands of the south side of the Olympic Mountains. The extent to which these additional gauges can be added will depend on the availability of personnel to deploy them.

Chehalis

A network of rain gauges will document the rainfall variability within the large Chehalis river basin. Existing COOP and RAWS sites are shown in Figure 7. These will be supplemented by 10 dual tipping bucket gauges and by an undetermined number of simple wedge gauges. These gauges will be placed at various elevations, and their locations will be determined by accessibility and data transmission considerations. The network is currently being designed and outreach by the UW Department of Civil and Environmental Engineering is ongoing to enlist observers to check the wedge gauges via the Community Collaborative Rain, Hail & Snow (CoCoRaHS) program.

4.4 Instrument maintenance and data transmission issues

Many of the planned and current ground instrument sites are extremely remote and maintenance and data transmission will require special considerations. Most importantly, personnel need to be identified to carry out manual tasks, and technology must be identified for automated data transmission wherever possible. Below is a list of requirements that must be satisfied at the various types of sites before the field phase of OLYMPEX.

- Lowland installations with access and power
    - Instrument maintenance whenever needed
    - Cell coverage needs verification and if insufficient, then satellite transmission necessary (i.e. CRN site will need satellite transmission)
- Lowland installations with access but no on-site power other than batteries
    - Battery swap every 1-2 weeks
    - Instrument maintenance as needed
    - Empty Pluvio (if installed) after 16” of precipitation, or every 2-3 weeks

- <u>High elevation installations with access and power</u>
    - Snow and rime removal off instruments after big snow events or every 2 weeks
    - Download data from computers
    - Check instrument alignment after big wind events
- <u>High elevation installation with limited access and no power other than batteries</u>
    - Site visits every 2-3 weeks– will require winter backcountry travel and possibly overnight stay
    - Snow and rime removal and digging out the trailer and instruments if snowpack is high
    - Empty Pluvio
    - Recharge batteries with generator if solar power was insufficient (i.e. no solar power during rainy/snowy periods)

Real-time data transmission is a potential problem at all ground sites. Cell phone coverage is limited, weak or non-existent throughout the Olympic Peninsula, especially in areas surrounded by tall trees and steep mountains. In many locations, satellite transmission may be the only viable option for monitoring the site real time. Therefore each site needs to be evaluated before the start of the project for data transmission issues.

5. Soundings

The backbone of the OLYMPEX dataset will be the storm thermal and wind structure revealed by soundings. Because the thermodynamic and dynamic conditions vary systematically as frontal systems make landfall over the Pacific Northwest, all specialized measurements of the OLYMPEX/RADEX dataset (surface observations, aircraft, radar) will need to be viewed in the context of where they are obtained in relation to the storm vertical structure prevailing at the time of observation. Without this contextual information it will be difficult to interpret the specialized data in terms of its implications for GPM and other satellite measurements in various synoptic and topographic situations. The 12 h soundings obtained by the NWS at Quillayute, WA, are too infrequent to provide this structure. During the CYCLES Project (Hobbs 1978), it was found that a time series of soundings at time intervals of 2-3 hours provided the background context to interpret aircraft microphysical measurements in relation to storm structure.

To obtain the time series of storm thermal and wind structure during OLYMPEX cases, soundings will be launched at time intervals of ~3 h at the NPOL radar site on the windward side of the Olympic Mountains and on the leeward side of the Olympics at University of Victoria, near the Canadian X-band site (48°25'22.00"N, 123°23'15.00"W). These sounding time series will allow us to place the ground-based measurements obtained in the Quinault Valley and at Hurricane ridge accurately into their larger-scale thermal and flow pattern context. The conditions upstream of the Washington coast during storm passages will be documented by dropsondes from the DC-8 aircraft (see Section 7.2 below).

Sounding units will be provided by Colorado State University for the Quinault sounding site and by Environment Canada at the Vancouver Island site. The Quinault station will be manned by graduate students and/or postdocs. Because the number of available expendable sondes is limited by budgetary constraints, decisions will need to be made daily regarding sounding frequency and when to begin and end rawinsonde launches at the two sites. These decisions will be part of the daily Operations Center discussions (Section 8.1).

Each sounding taken will be plotted using standard software and made available to the Operations Center as both an image and raw digital data as soon as the sounding has been completed. Personnel for creating the sounding plots have yet to be identified.

6. Ground-based radars

A variety of radars will be deployed at the locations shown in Figure 14. Because of mountains, forests, and land-use restrictions, very few sites are suitable and available for the various radars. The sites shown in this Figure have been (or will be) surveyed to determine that they are appropriate for the type of radar to be operated at that location. The basic strategy is that the NWS WSR-88D radars on the Pacific Coast at Langley Hill, WA, and at Camano Island, WA, will provide the horizontal precipitation patterns via their standard tilt-sequence PPI scans. The NPOL radar and Environment Canada X-band radar (SELEX METEOR 50DX) will provide detailed radar coverage in RHI sectors as shown in Figure 14. NPOL will execute RHI sectors over both the Pacific Ocean for upstream conditions and over the Quinault Valley for conditions over the complex windward-side terrain. Three Micro Rain Radars (MRRs) and a Doppler on Wheels radar (DOW) will be located under the eastern NPOL RHI sector to provide information at low levels, below the beam of NPOL. Similarly, the Canadian X-band radar will provide detailed coverage on the leeside by conducting sector scans over the Hurricane Ridge site, where one MRR will be located. This radar coverage will document in detail the structures that will be observed by the GPM instruments (albeit, in less detail) and will document how frontal, orographic, and convective precipitation processes will be determining the precipitation profiles observed by GPM. The basic characteristics of the OLYMPEX ground-based radars are listed in Table 2, and further details are discussed below.

6.1 S-band radars (NPOL and WSR-88Ds)

The broad background of reflectivity, radial velocity, and dual-polarimetric variables will be provided by the operational NWS WSR-88D operational radars at Langley Hill, WA, and Camano Island, WA. These radars have a wavelength of 10 cm (S-band), peak power of 750 kW, and a beamwidth of ~1°. The Langley radar tilt sequence mode includes an elevation angle at 0.2°. Because they are operational radars of the NWS, the Langley Hill and Camano Island radars will be running throughout the time period of the project.

The site for the NASA/NPOL radar has been surveyed and preparations for siting are underway with approval of the Quinault Nation (see Figure 15). This radar is S-band, Doppler, and dual-polarimetric. It has peak power of 850 kW and a beamwidth of 0.93°. NPOL will execute RHI scans in two sectors, as indicated in Table 3. One sector is located over the ocean. It will contain 40 RHIs, bounded by azimuths approximately 210° and 326°. These azimuthal limits may be adjusted slightly clockwise or counterclockwise according to meteorological conditions at the discretion of the NPOL Radar Scientist. Each RHI will run from 0° to 45° elevation. The other sector is located over the Quinault Valley, bounded by azimuths of 30° and 60° and will contain 16 RHIs from 0° to 45° elevation. The RHIs sectors will be interspersed with PPI scans at three low-level elevation angles of 0.5, 1.5, and 2.5°. This sequence will take ~20 minutes and will be repeated continuously throughout all rainy periods. Site surveys confirm that these sectors have open views for scanning. Beam blocking is minimal. The NPOL will operate from 1 November–21 December 2015 and from 3–15 January 2016.

6.2 X-band radars (DOW and 50DX)

A dual-polarimetric Doppler Radar on Wheels (DOW) is being deployed under an NSF project of R. Houze. The DOW will be placed in the Quinault Valley, within the eastern RHI sector of NPOL. It will scan in RHI mode up and down the valley to fill in dual-polarimetric signals and radial velocity data below the lowest beams of NPOL. The DOW (version 6 or 7 to be used in OLYMPEX) is truck mounted and operates at a frequency of about 9.4 GHz (wavelength ~3.2 cm), with a beamwidth of 0.93° and peak power of 500 kW. The DOW will operate from 10 November through 22 December 2015 and from 3–17 January 2016.

Environment Canada's 50DX will operate on the southern tip of Vancouver Island (at Albert Head, 48°23'13.62"N, 123°28'40.95"W). It will scan over the Hurricane Ridge OLYMPEX ground site to provide radar coverage on the leeside of the Olympic Mountains that will complement the windward side coverage by NPOL and WSR-88D. The 50DX will execute a series scans similar to that at NPOL, but with only one RHI sector, which will be centered on the azimuth of Hurricane Ridge. As at NPOL, the RHI scans will be interrupted for low-level PPI scans at intervals of ~10-20 min. The 50DX will be deployed together with an X-band Precipitation Occurrence Sensor System (POSS) bistatic radar. The POSS provides information on surface precipitation intensity and its associated microphysical characteristics. The Environment Canada operation will take place from 1 November – 22 December and from 3–17 January 2016.

6.3 Ka- and Ku-band dual-frequency dual-polarimetric radar system (D3R)

The NASA D3R radar systems have wavelengths in the Ku and Ka ranges, similar to the radars on GPM. The Ku frequency is 13.91 GHz (wavelength 2.16 cm); the Ka frequency is 35.56 GHz (wavelength 8.43 mm). Both radars are dual polarimetric. At Ku (Ka) the peak power is 200 W (40 W), and the beams are matched to sample a common pulse volume at a width of 1°. The goal of the D3R deployment is to provide ground-based measurements that determine what the GPM radars may or may not be missing in midlatitude winter storms. This radar system will be located near NPOL and will be operated in a scanning mode that is compatible with NPOL. This scanning will consist of RHIs with elevation angles running from 0 to 90° in sectors both to the west (toward the ocean) and east (toward the Quinault Valley). These RHIs will be interspersed with a few low-level PPI tilts (which will be especially useful in determining the light rain measurements favored by the higher frequencies of the radar). This scanning will be done on the same schedule as the NPOL scanning. The D3R operation will coincide with the NPOL operation: 1 November – 22 December and 3–17 January 2016.

6.4 K-band Micro Rain Radars (MMRs)

OLYMPEX will deploy four vertically pointing Micro Rain Radars (MRRs) at the sites indicated in Figure 14. These radars will fill in reflectivity and drop-size distribution information at the lowest levels below the beams of the scanning radars. The plan is to set the MRRs to 100 m resolution to give 3 km of sampling depth, except at Hurricane Ridge (~1.7 km above sea level), where a 60 m resolution will be used to yield ~1.8 km of sampling depth.

Three sites will document the vertical structure of the precipitating clouds on the windward side of the Olympic Mountains. These sites will be within the region of Quinault River sector scans of NPOL at three different distances from NPOL. These sites are at the Quinault Fish Hatchery, which is west of Lake Quinault, the CRN site, just east of Lake Quinault and a third site, which could be either at Neilton Pt, the southern ridge defining the

Quinault Valley, or further east up the Quinault from the CRN site. The MRR operates as a continuous wave radar at 24 GHz, which corresponds to a wavelength of about 1.5 cm. Two of the MRR radars, at Hurricane Ridge and the Quinault Fisheries, will operate from 1 November 2015 through sometime in the spring of 2016; the other two will operate from 1 November through 15 January 2016.

6.5 Radar operating schedules

Radar operations at NPOL and D3R will be governed by the NASA personnel regulations in Table 4. The engineering staff will work 8-hour shifts, and the radar scientists will work 12 hour shifts. Using the guidelines in Table 4, it is expected that the NPOL can operate for ~7 consecutive days before a down day is required. Down days will need to be scheduled as part of the daily meeting deliberations (Section 9.2). The DOW radar operates under less stringent rules but will be kept on the same schedule as NPOL and D3R. The Environment Canada 50DX is also expected to observe the same schedule. Part of the daily decision making at the Operations Center will be when time off will occur at the NPOL, D3R, DOW, and EC radars (see Section 9).

7. Aircraft program

7.1 Time period of the aircraft program, participating aircraft, instrumentation, and no-fly rules

The OLYMPEX aircraft are the NASA DC-8 and the NASA/UND Citation. The dates that these two aircraft can fly OLYMPEX missions are 10 November 2015 – 21 December 2015, inclusive; i.e., the DC-8 and Citation will not be available to OLYMPEX on 9 November or 21 December. Table 5 lists the instruments likely to be on each aircraft. The DC-8 will function as a proxy for the satellite radar and passive microwave measurements. In addition, the DC-8 will launch dropsondes over the ocean, which will help describe the thermodynamic and wind environment of incoming storms, upstream of the ground-based rawinsonde sites (Figure 1). These soundings will also be important for evaluating the robustness of temperature and water vapor assumptions in GPM algorithms. The Citation will provide in situ microphysics. The RADEX aircraft is the NASA ER-2. From the OLYMPEX standpoint, it will also augment the satellite proxy measurements with radar and passive microwave measurements. The RADEX aircraft operating schedule is from 17 November to 13 December, inclusive. If certain instruments are down, then no-fly rules will be implemented (Table 6.)

7.2 Basic flight modules

Flight modules are the generic flight patterns that will be employed during the deployment of an aircraft. The geometry and details of the modules (end points, turn points, etc.) can be adjusted during flight planning or in flight by aircraft operators in consultation with the OLYMPEX Operations Coordinator and OLYMPEX Flight Director (see Section 8). It is nevertheless important to use similar flight modules from case to case so that at the end of the field phase the aircraft data will form a robust statistical sample for each of the three storm sectors (Figure 6).

Figures 16-26 illustrate the generic flight modules that can be used by the ER-2, DC-8, and Citation. Note that WPT refers to a waypoint, i.e. a specific location where a flight track changes. The following terminology is used:

- “Hit WPT on a XXX hdg” means that waypoint must be approached on that specific heading, and the heading must be held for the leg that starts at that WPT.

- "Turn at WPT" or "Fly to WPT", means that waypoint is the end target of the leg, turn before reaching it to make a curve on the inside of the two connecting legs.
- "Overshoot WPT" means overshoot WPT and THEN turn or do whatever is necessary to take care of the next step.

Figure 16 shows the general areas in which flights will be conducted. Figure 17 shows two options for calibration flights. Figures 18-25 show the primary flight modules to be deployed depending on the weather situation. The Flight Science Directors for the day (see Section 8 below) will choose the appropriate flight patterns in pre-flight planning and in real time during flight operations. Figure 26 shows examples of flight tracks to be employed to coordinate with GPM overpasses. Figure 27 shows flight patterns to be executed by the Citation aircraft to obtain cloud microphysical data.

For OLYMPEX DC-8 flight tracks will be executed at high altitude so that radar and passive microwave remote sensors on these two aircraft will obtain measurements similar to the GPM satellite. For RADEX, ER-2 flight tracks will emphasize flights over the ocean and whenever possible fly along the same tracks as the DC-8 as near as possible to the same times but not necessary exactly stacked vertically. One exception is that it will be important to stack the ER-2 and DC-8 as close as possible in time for simultaneous measurements with the CoSMIR and AMPR instruments. Both OLYMPEX and RADEX seek microphysical information at the lowest temperatures that can be sampled by the aircraft and data on the variation of microphysical processes through the melting layer. For these reasons, the Citation needs to obtain cloud microphysical data at various in-cloud temperatures. Figure 27 shows two strategies for multi-altitude sampling by the Citation. Flight Science Directors (Section 8) will advise the Citation regarding when and where to obtain the Lagrangian spiral data using the pattern illustrated in Figure 27b. The spiral should approximate the fall trajectory of an ice particle undergoing melting, so the prevailing wind profile will need to be considered in setting up such patterns. The Citation has shorter flight duration than the DC-8 and ER-2 (Table 5). However, it has the capability to land, refuel, and obtain a second set of data within a given storm so the module does not extend over as large a region as the ER-2 and DC-8 modules.

7.3 Aircraft operating rules

The DC-8 will operate with the following rules. Daytime flying is preferred. The DC-8 can operate up to 3 consecutive days. A full day off ("hard down day") is required every 7 days. The Citation crew duty day is 16 hours preceded by 10 hours rest. The Citation can operate for a maximum of 14 consecutive days. The Citation flights will be embedded within the DC-8 flight window. DC-8 flights will be ~5-8 h in duration. The ER-2 flights will also be embedded within the DC-8 flight window whenever possible. The ER-2 will only fly in daytime conditions, and will generally not be able to fly on consecutive days. The Operations Coordinator will inform the DC-8 and other aircraft teams a day in advance with a fly/no fly decision, after the daily planning meeting (Section 9). When a decision to fly is made, the Operations Coordinator will inform the teams with an updated and detailed flight plan by 6 pm the night before a morning take off. If a switch is made from day to night (or night to day) flying, there will be gap of approximately 30+ hours when flights cannot occur. Further note: The FAA requires 72 hours notice for CPL and dropsonde measurements.

7.4 Scorecard

To maintain a cumulative assessment of progress toward OLYMPEX and RADEX goals, an aircraft mission "scorecard" will be updated daily and presented at the 10:00 am daily meeting. This scorecard will assess the sampling by storm sector:

- Prefrontal
- Frontal
- Postfrontal

and by geographical region:

- Upstream over the ocean
- Windward side (over the Quinault Valley)
- High terrain
- Leeside (over the Hurricane Ridge and Vancouver Island sites)

The format of the scorecard is shown in Table 7, with numbers showing the target distribution of flight hours that would achieve the goals of OLYMPEX and RADEX. The primary objective is to obtain substantial samples of aircraft data for each combination of storm sector and geographical region. On any given mission, some combination of the flight patterns in Figures 18-25 will be used to accomplish these storm sector/geographical region objectives. A cumulative scorecard with the actual number of flight hours obtained in each category will be maintained throughout the project. It will be discussed at the daily meeting (Section 9.2). The scorecard will thus reflect the number of hours of data obtained by each aircraft for each storm sector over each geographical region. A more detailed tally will be kept by the OLYMPEX and RADEX teams to determine if the flight hours on the scorecard have achieved specific types of objectives. One special case of note is that if a potentially flooding storm occurs over the Chehalis River basin (Figure 2), the flight tracks in Figures 18-25 will be adapted to that region.

In addition to the storm sector/geographical region flights, under-flights of GPM overpasses will also be carried out. Because overpasses will be brief, we will carry out these under-flights by breaking out of one of the standard flight patterns to fly one of the patterns in Figure 26.

Besides storm sector/geographical region flights and under-flights of GPM overpasses, several calibration flights will be performed as in Figure 17.

An additional scorecard will be maintained for each day of OLYMPEX, regardless of whether flights are undertaken. This scorecard, shown in Table 8, tabulates the number of hours of data obtained in certain types of phenomena. It will also show the number of aircraft hours obtained for each type of phenomenon. The RADEX project will maintain a separate scorecard for their objectives.

8. Airborne and ground personnel and responsibilities

OLYMPEX and RADEX will have the following science personnel with specific assignments:

- <u>Operations Coordinator</u> (Rotated among Houze, McMurdie, and Petersen)—responsible for chairing the daily meeting at which project plans will be made; maintain overview of planning for the next 2-3 days; write detailed daily summaries of weather, data collection, and likely scientific value of the day's data. The Operations Coordinator will maintain the aircraft scorecard, described above.

- Flight Communications Manager (Jan Nystrom)—Liason between OLYMPEX and RADEX Flight Science Directors and aircraft, for all flights. Will work at the Operations Center. He will coordinate proposed operations with military and civil authorities as necessary, and during missions will maintain communication with and coordination of the aircraft in their execution of project objectives. He will keep the aircraft apprised of changes to flight plans requested by the OLYMPEX and RADEX Flight Directors. Mission coordination/communication will be accomplished with the DC-8 and Citation via chat and with the ER-2 by radio.
- Flight Science Director for OLYMPEX (Rotated among Zipser, Rutledge, Nesbitt, McFarquhar, Munchak, Lang, Braun, Cecil, Colle)—Responsible for planning and executing DC-8 and Citation flights decided upon by the daily meeting; communication of the day's plans to the managers of the DC-8 and Citation aircraft; coordination of flight planning with the RADEX flights whenever ER-2 flights are planned; specific responsibilities include deciding on take off times, flight track type (Figure 16-26), waypoints, adjusting waypoints in real time, communicating these changes to the Flight Communications Manager; monitoring of flights throughout planning, take off, in-flight, landing and debrief. During the in-flight period, the Flight Science Director will monitor the progress of the flight to identify changes and/or adjustments to flights in real time and will convert these changes to new waypoints to be passed to the aircraft via the Flight Communications Manager.
- Flight Science Director for RADEX (Mace, Marchand, …)—Similar to Flight Science Director for OLYMPEX except for the ER-2
- NPOL Scientist (Rotated among Wolff, Hence, Barnes, Brodzik, Rowe, Rasmussen, Dolan, and Zuluaga)—Assist with the operation of the NPOL radar in 12-hour shifts; make minor adjustments to the boundaries of RHI sectors as requested by the Operations Coordinator; maintain notes of phenomena seen by NPOL; assist with rawinsonde launches as needed.
- DOW Scientist (Rotated among several students, postdocs, and staff)—Assist with the operation of the DOW radar in 12-hour shifts; maintain notes of phenomena observed by the DOW.
- Environment Canada operations (Led by D. Hudak and P. Rodriguez)—similar to NPOL operations
- Sounding operations (Led by S. Rutledge and P. Ciesielski and operated by Colorado State personnel)—Launch sondes at intervals requested by the Operations Coordinator as a result of the daily planning meeting.
- Ground instrument operations (Led by M. Wingo, J. Zagrodnik)—Monitor and maintain instruments at all ground sites.
- Chehalis rain gauges (Bart Nijssen)—Collection of rain gauge data in the Chehalis region.
- Forecasting operations (Led by L. McMurdie with a crew of graduate student forecasters from University of Washington and University of Utah)—Monitor weather around the clock and provide forecasts and briefings for the daily planning meeting, pre-flight briefings and afternoon updates.

Table 1. List of ground instruments other than radars

Name	Elev-ation (ft)	Instruments: X = currently deployed, P= Planned, P*= Possible or under discussion							Power	Access
		PIP	2D VD	Parsi-vel	Pluvio	Hot Plate	Dual Tipping Gauge	Single Gauge		
Lee Side										
Hurricane Ridge	5140	X		X		X			Yes	Road, in winter
Windward side										
Wallace Cabin	15			P			P	X	Yes	Road
Kalaloch, NPS	39			P			P		Yes	Road
Seed Orchard	255			P			P		No	Road
Fish Hatchery	170		P	X			X		Yes	Road
Amanda Park	290		P	P			P		Yes	Road
Norwood S. Shore	220			P			P		No	Road
Bunch Field	380			P			P	X	No	Road plus walk
CRN Site	285		P	P					Yes	Road
Graves Creek	563			P				P	No	Road plus Trail
O'Neil Creek	1200							P	No	Trail
Prairie Creek	1750			P			P		No	Road, in winter.
Neilton Pt	2156	P*	P	P	P	P*			Yes	Road, in winter
Upper Quinault	2033			P	P				No	Trail
Wynoochee Trailer	3160			X	X				No	Road plus trail

Table 2. Ground-based radars to be deployed in OLYMPEX. See text for further details.

Radar	Location	Frequency	Scanning mode	Doppler	Dual-Pol.
NPOL	Tahola, WA	S-band	RHI sectors interspersed with low-level PPIs	yes	yes
D3R	Tahola, WA	Ka/Ku-band	RHI sectors interspersed with low-level PPIs	yes	yes
50DX	Albert Head, Vancouver Island, BC,	X-band	RHI sectors interspersed with low-level PPIs	yes	yes
DOW	Lake Quinault	X-band	RHI sectors, up- and down-valley	yes	yes
MRR	Hurricane Ridge	K-band	Vertically pointing	yes	no
	Fish Hatchery				
	CRN site				
	Neilton Point				
NWS 88-D	Camano Island, WA	S-band	Operational PPIs down to 0.5 degrees	yes	yes
	Langley Hill, WA	S-band	Operational PPIs down to 0 degrees	yes	yes

Table 3. Scanning procedures for OLYMPEX radars

(a) NPOL

	Task	Time (MM:SS)	# Angles	Azimuth (°)	Elev (°)	Range (km)	Bin spacing (m)
ONE CYCLE	RHI_A* (Pacific sector)	12:22	40	210, 213, 216, 219, 222, 225, 228, 231, 234, 237, 240, 243, 246, 249, 252, 255, 258, 261, 264, 267, 270, 273, 276, 279, 282, 285, 288, 291, 294, 297, 300, 303, 306, 309, 312, 315, 318, 321, 324, 327*	0-45	0-135	125
	RHI_B (Quinault sector)	4:52	16	032.5, 035, 037.5, 040, 042.5, 045, 047.5, 050, 052.5, 055, 057.5, 060, 062.5, 065, 067.5, 070	0-45	0-135	125
	PPI	1:42	3	0-360	0.5, 1.5, 2.5	0-135	125
	"Birdbath" scan (ZDR calibration)	1:33	2	0-360	90		125
	(~19 min/cycle x 3 cycles) + 1.5 min for birdbath scan ~= 1hour						
	*Angles may be rotated clockwise or counterclockwise according to meteorological conditions at discretion of the NPOL Radar Scientist						

(b) D3R

Scan Name	El. Angles (°)	Az. Angles (°)—range and step	Samples per range bin	Effective PRF (Hz)	Scan Speed (°/sec)	Approx slew time (sec)	Approx Time (min)
PPI	0.5,1.5,2.5	220 scanning CW to 130	128	2000	8.00	6	1.9
RHI Sector A	0 to 90	(222,327:3)	128	2000	5.00	1	11.7
RHI Sector B	0 to 90	(30,60:2)	128	2000	5.00	3	5.3
Birdbath x 2	90	0 to 359	128	2000	6.00	3	2.0
						Total	21.1

Table 3. (cont.)

(c) DOW

	Task	Time (MM:SS)	Angles	Azimuth (°)	Elev (°)	Range (km)	Bin spacing (m)
ONE CYCLE	RHI_A upstream into valley	:00	20	65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85	-60	0-50	75-125
	RHI_B downstream to NPOL	:00	20	234, 235, 236, 237, 238, 239, 240, 241, 242, 243, 244, 245, 246, 247, 248, 249, 250, 251, 252, 253, 254	-60	0-50	75-125
	PPI	:30	1	0-360	.0	0-50	75-125
	"Birdbath" scan (ZDR calibration)	:00	3	0-360	5		75-125
	*Angles may be rotated clockwise or counterclockwise according to meteorological conditions at discretion of the PIs						

(d) 50DX

	Task	Time (	# Angles	Azimuths in sector centered on Hurricane Ridge (°)	Max Elev (°)	Range (km)	Bin spacing (m)
ONE CYCLE	RHI sector over NE side of Olympic Mountains	~15 min	20	0-45 elevation sweeps at1.5° azimuth interval, sector centered on Hurricane Ridge	45	0-60	125
	PPI	~5 min	~10	0-360 azimuthal sweeps, in elevation steps	~45	0-60	125

Table 4. NASA rules for scheduling personnel at NPOL and D3R radar.

Maximum Work Period Hours	• 16 hours • 20 hours w/waiver (Campaign Manager has a 1-time waiver authority)
Maximum Hours in a 7day period	• 72 hours • 84 hours with waiver (Campaign Manager has a 1time waiver authority)
Maximum Consecutive Days Worked	• 13 days (may be extended to 17 days during countdowns with waiver approved only by the Director of Code 800)
Minimum Time Off Between Work Periods (Hours)	• 8 hours if work period is less than or equal to 12 hours • 10 hours if work period is greater than 12 hours • 24 hours after working maximum consecutive days
Waiver Authority	• Director of Code 800 • One time authority given to Campaign Manager (does not include the authority to authorize a change to the maximum consecutive days worked.)

Table 5. Instruments on aircraft participating in OLYMPEX/RADEX

Aircraft	Primary instruments	Measurements	Duration	Speed (kt)	Instrument PIs
DC-8	CoSMIR	Passive microwave at 50, 89, 165.5, 183.3+/-1,183.3+/-3, 183.3+/-8 GHz Cross track/conical scan, 0.7 km footprint	8-10 h	~400 above 20 kft ~380 at 10-20 kft ~250 below 10 kft	Kroodsma
	APR2 or 3	Ku- and Ka-band radar, Doppler (0.4 m/s prec), swath ± 25°, 0.7-0.8 km footprint from 10 km altitude, sensitivity: ~0 dBZ (Ku), –17 dBZ (Ka) (also W-band, dual pol if APR-3)			Durden/Tanelli
	AVAPS Dropsondes	Vaisala RD94- p, T, RH, wind			Hoch
ER-2	AMPR (radiometer)	10.7, 19.35, 37.1, 85.5 GHz; footprints 2.8, 2.8, 1.5, 0.6, respectively, at 20 km		Sample 400 kts at 65 kft	Roberts/Lang G. Heymsfield G. Heymsfield G. Heymsfield Diner/Seidel Platnick McGill
	HIWRAP (radar)	13.91 GHz, 35.56 GHz (dual-pol. (LDR); nadir pointing), footprint ~1 km at 20 km			
	EXRAD (radar)	9.4 GHz (nadir); 9.6 GHz (scanning; 25 km swath at 20 km alt.); footprint 1.2 km at 20 km			
	CRS (radar)	94.15 GHz (nadir pointing); footprint ~0.16 km at 20 km			
	AirMSPI	Eight band radiometer (355, 380, 445, 470, 555, 660, 865, 935 nm); push broom scan, spatial resolution 10-25 m depending on scan mode.			
	CPL (lidar)	1064 (50 μJ), 532 (25 μJ), and 355 (50 μJ) nm; 5 kHz PRF; footprint ~ 30 m at 20 km			
	eMAS	Extended MODIS simulator, 38 spectral bands (0.4–14 μm); footprint 50 m at 20 km			
Citation	King Hot Wire Probe	Liquid water, 0.02–5.0 g m^{-3}		Sample 160 kts MOCA to ~35 kft Cruise 175 kts	Poellot A. Heymsfield
	CloudDroplet Probe (CDP)	Cloud droplet size distribution, 2–50 μm range			
	2D-S	Particle images, 10 μm–1280 μm			
	HVPS-3 (2 units)	Particle images, 150 μm–1.92 cm; One horizontal and one vertically-oriented instrument			
	CPI	Cloud particle imager; particle imagery at 2.3 m resolution			
	CSI	Cloud water content, 0.02 - ~1.0 g m^{-3}			
	2DC	Particle images, 30–960 μm			
	Nevzorov	Total water content, 0.02 – ~1.5 g m^{-3}			
	Rosemount icing probe (RICE)	Supercooled water detection			

Table 6. Fly/no-fly decision table.

DC-8 Fly Rule	APR3 Ku *or* Ka DOWN (≤ 2 day repair[a])	APR3 W-Band DOWN (≤ 1 day repair[a])	CoSMIR 2 freq. ≥ 89 GHz DOWN (≤ 2 day repair[a])	UND down < 2 days; or Key probe down < 1 day	Radar outage (NPOL/ D3R)
NO FLY	**a**	**a**	**a, b**	**a, c**	**d**

a Operations Coordinator (OC) discretion always applies, but decision to fly without one or more frequencies or a probe, necessarily evolves with campaign duration and nature of the problem. Ka and Ku frequencies are a larger priority than W-Band and hence more allowance for downtime should be considered.

b The most critical frequencies on CoSMIR are the ice scattering channels; all else is at OC discretion.

c Here the implication is that UND Citation or a critical probe on the aircraft can be fixed quickly. So, early in campaign (first 2 weeks), DC-8 NO FLY *unless* GPM Overpass with precip; *After* first two weeks, this section no longer applies- and line (d) below applies, especially if the issue is a probe. Key probes: *2D-S, HVPS3 (both at same time), CSI*.

d OC discretion (mission/situation dependent)

Table 7. Aircraft scorecard for determining progress toward OLYMPEX and RADEX goals

	Pre-Frontal			Frontal			Post Frontal			Other[*]		
	DC8	**ER2**	**Cit.**	**DC8**	**ER2**	**Cit.**	**DC8**	**ER2**	**Cit.**	**DC8**	**ER2**	**Cit**
Upwind / Off Shore	10	10	8(3)[+]	10	12	10 (7)	10	10	10 (5)	2	4	2
Windward	10	6	9	10	6	9	10	6	9			
High Terrain	3		3	3		3	3		3			
Leeside	3		3	3		3	3		3			

[*]other includes clear sky off shore radar calibration and surface emissivity, as well as potential GPM/A-train coincidences (any zone)

[+]bracket indicates RADEX contribution to UND flight hours.

Table 8. Hours of OLYMPEX data by characteristic (blue), frontal sector (green), and geography (brown). Aircraft in parentheses. Daily and cumulative.

	Relative to storm structure				Relative to ocean and terrain			
	Pre-frontal	Frontal	Post-frontal	Clear	Ocean	Wind-ward	High terrain	Lee
Light rain (< 1 mm/hr or <25 dBZ)	# (#)							
Moderate rain (1-5 mm/hr or 25-35 dBZ)								
Heavy rain (>5 mm/hr or >35 dBZ)								
Snow over mountains								
Convective cells								
Variable 0°C height								
Melting layer profile								
Warm case								
Cold case								
Chehalis flood								
Quinault high water (NWS advisory or warning))								
Calibration								
GPM Core overpass								
GPM Constellation overpass								

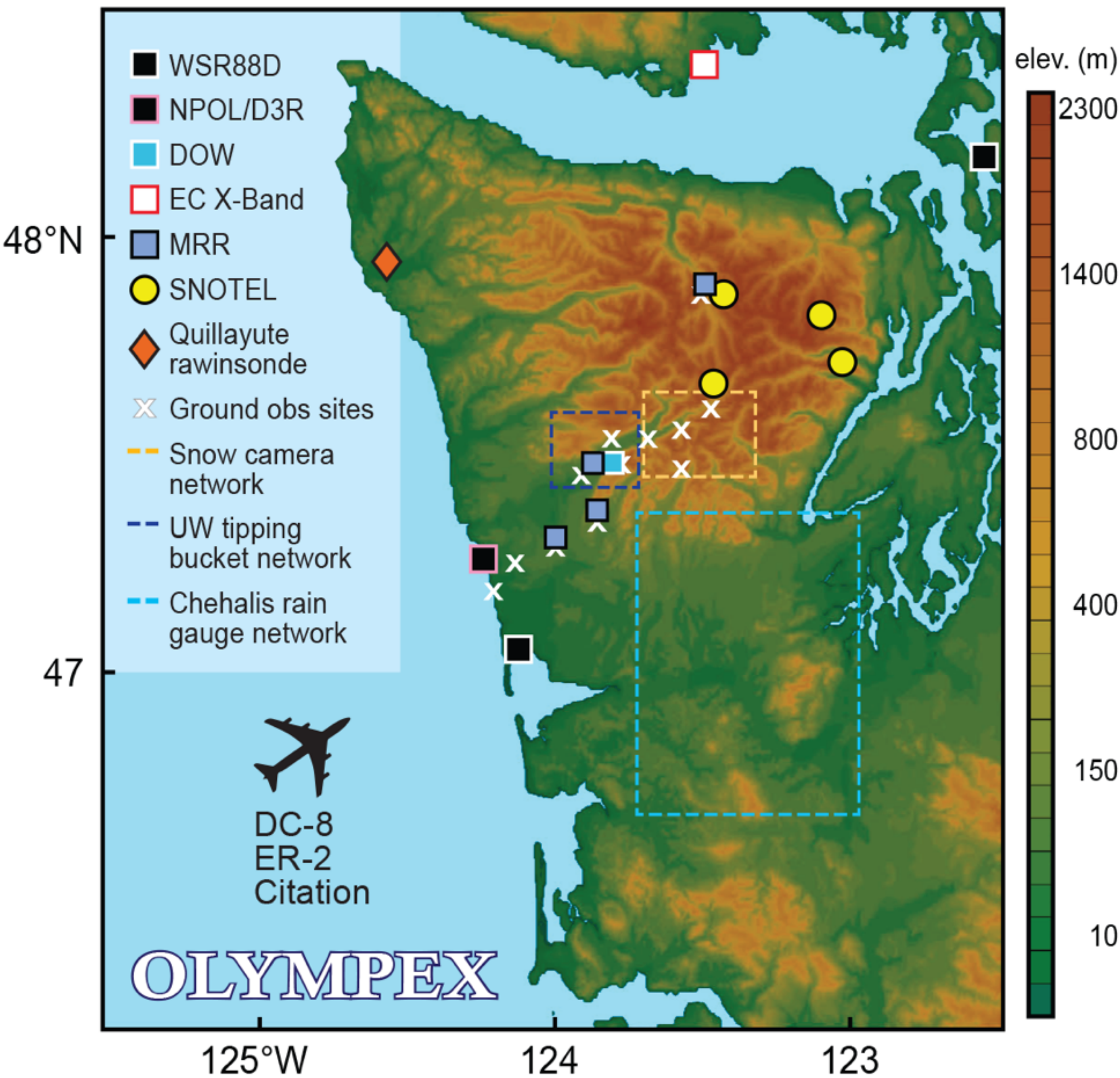


Figure 1: Map of ground observations for OLYMPEX. Radars shown as squares, SNOTEL sites as circles, key ground observing locations as X's and rain and snow networks as dashed boxes.

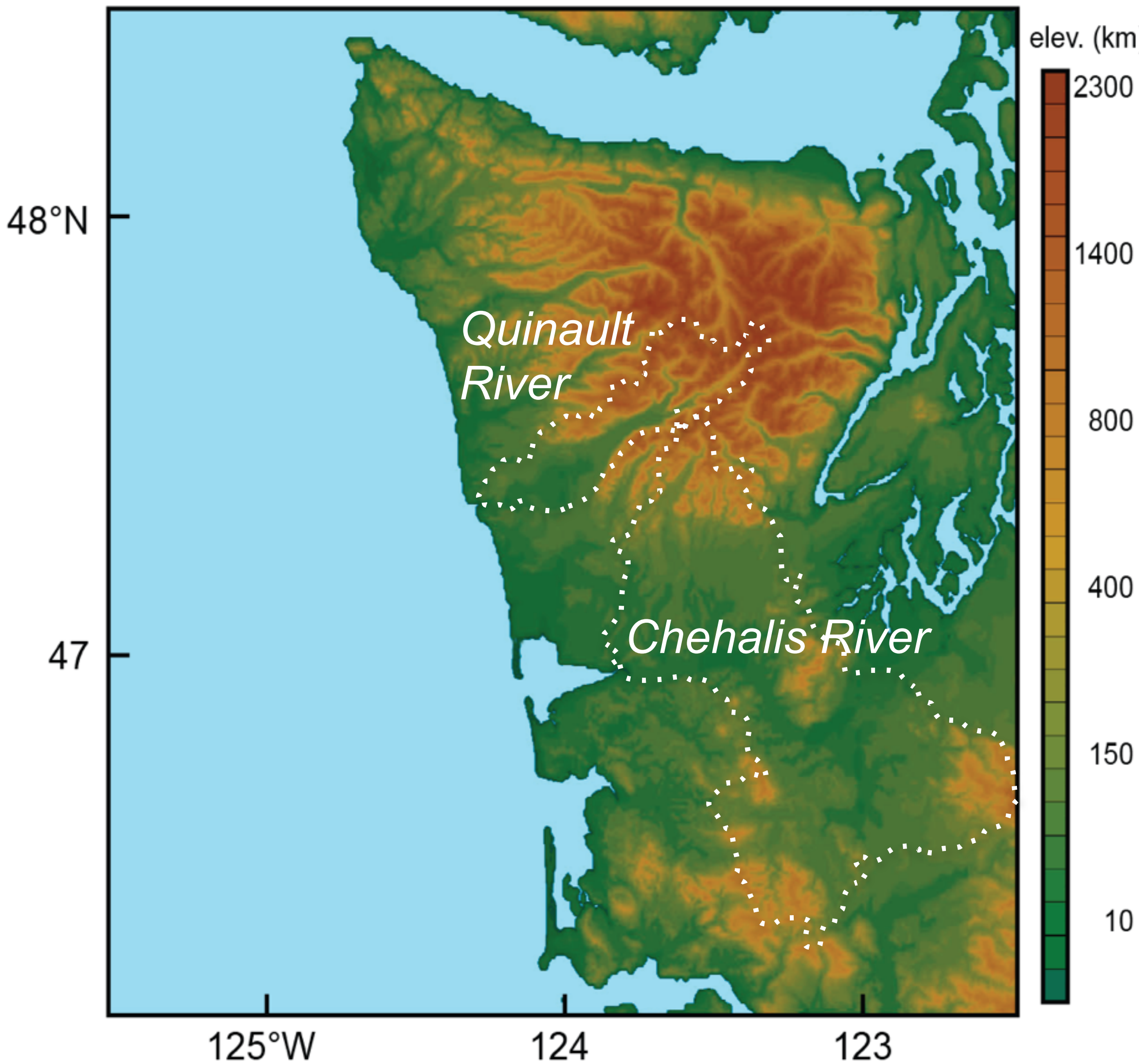


Figure 2: Map showing the location of the two river basins, the Quinault and the Chehalis, which will be the focus for hydrology for OLYMPEX.

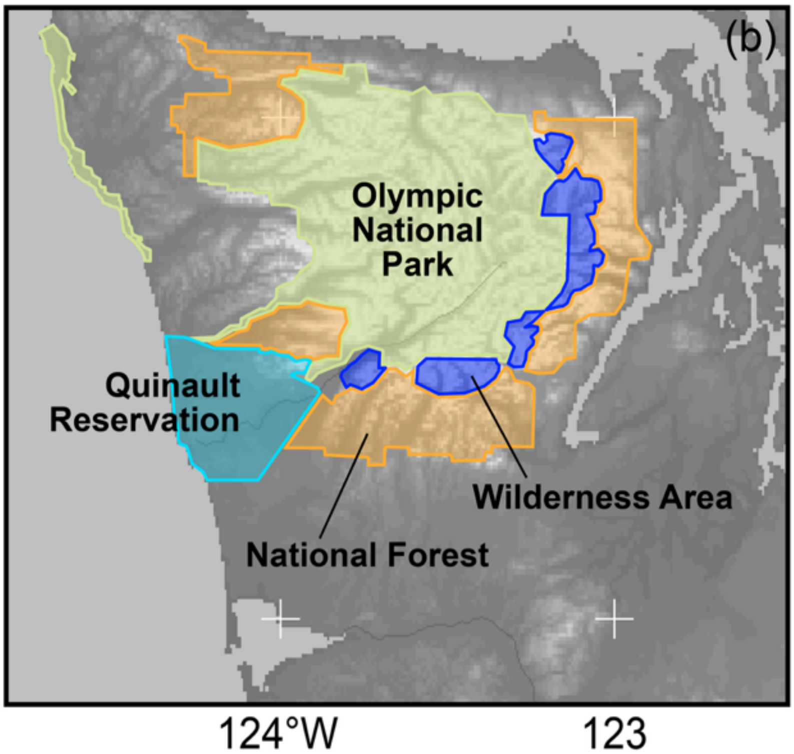


Figure 3: Map of the Olympic Peninsula with the locations of the boundaries for the Olympic National Park, the US National Forests and Wilderness areas and the Quinault Reservation.

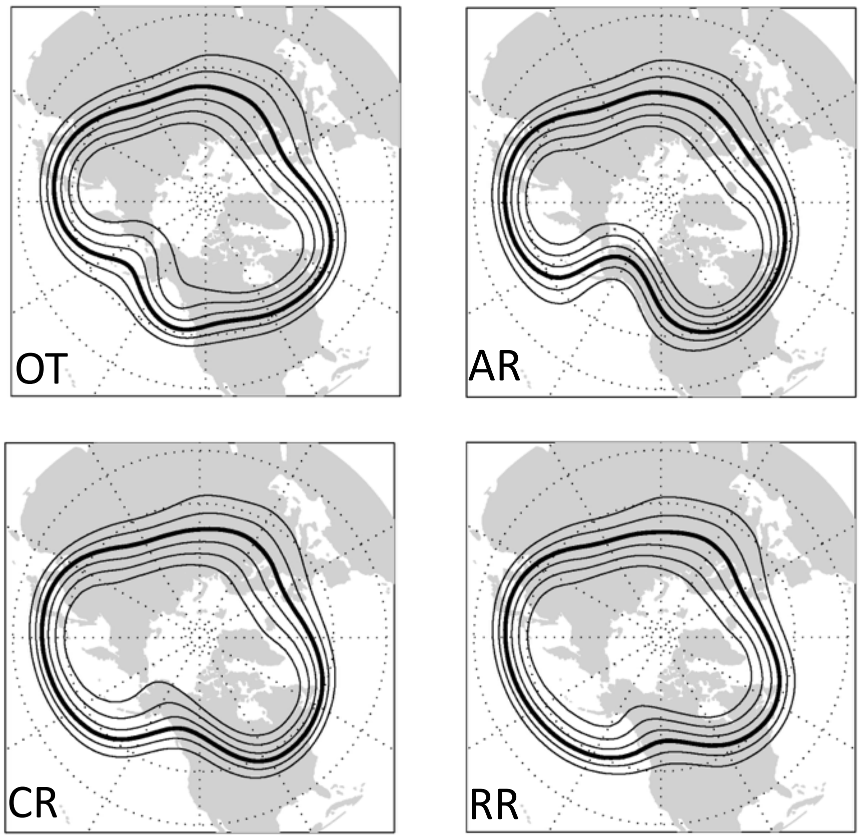


Figure 4: Four dominant regimes of the 500 hPa geopotential height patterns: Offshore Trough (OT), Alaska Ridge (AR), Coastal Ridge (CR) and Rockies Ridge (RR).

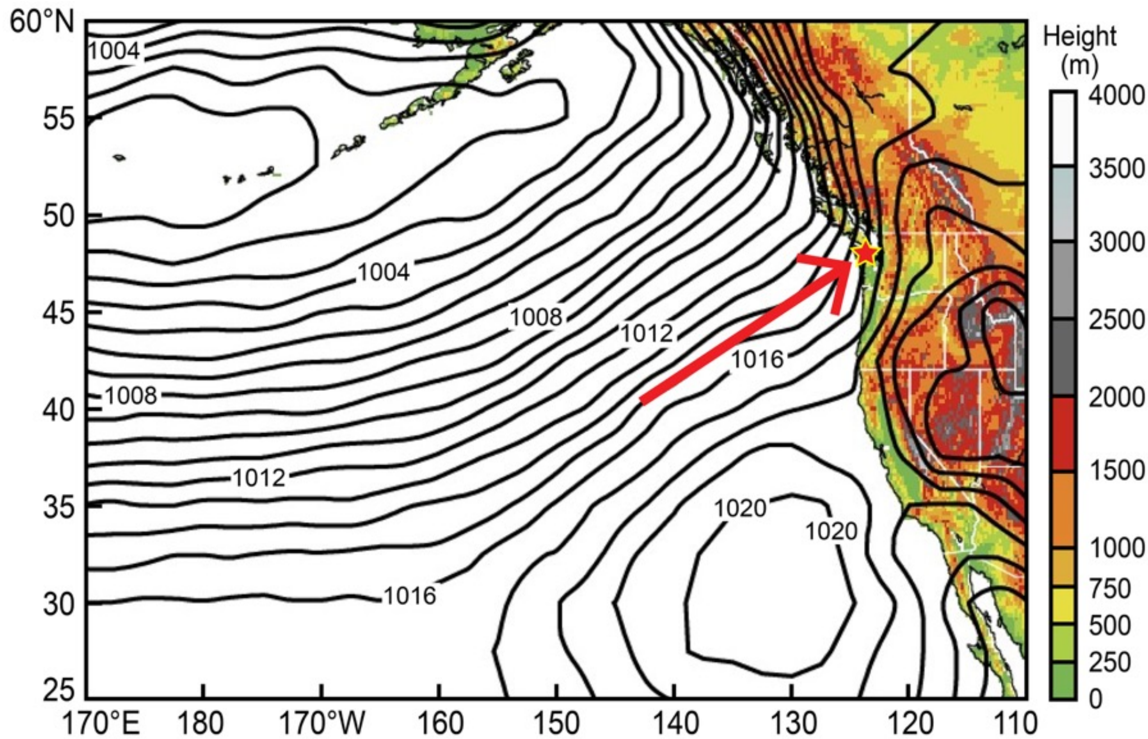


Figure 5: Long-term mean sea level pressure for the period November – February from Reanalysis Data (1979 – 2012). Star indicates location of the Olympic Peninsula and the arrow highlights the direction of the low-level flow.

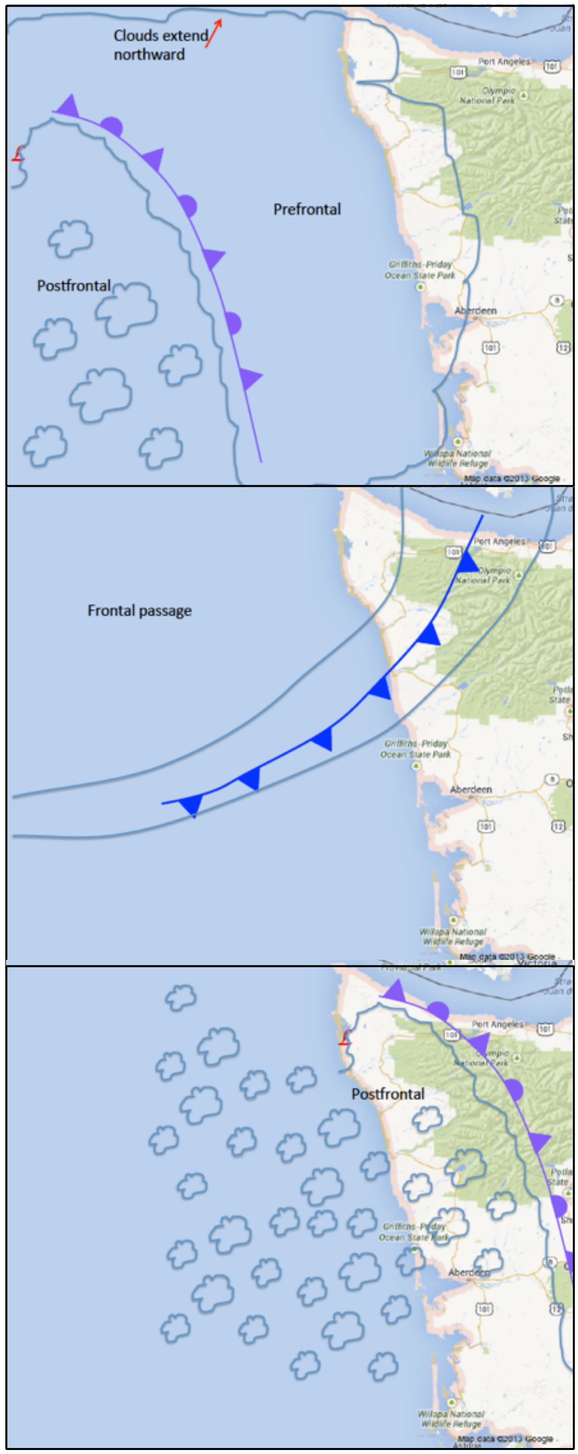


Figure 6: Idealized depiction of the three sectors of a typical midlatitude cyclone. Cloud outlines as seen from satellite imagery shown in blue, standard frontal symbols shown in blue (cold front) and purple (occluded front): Prefrontal (top), Frontal (middle) and Post Frontal (bottom).

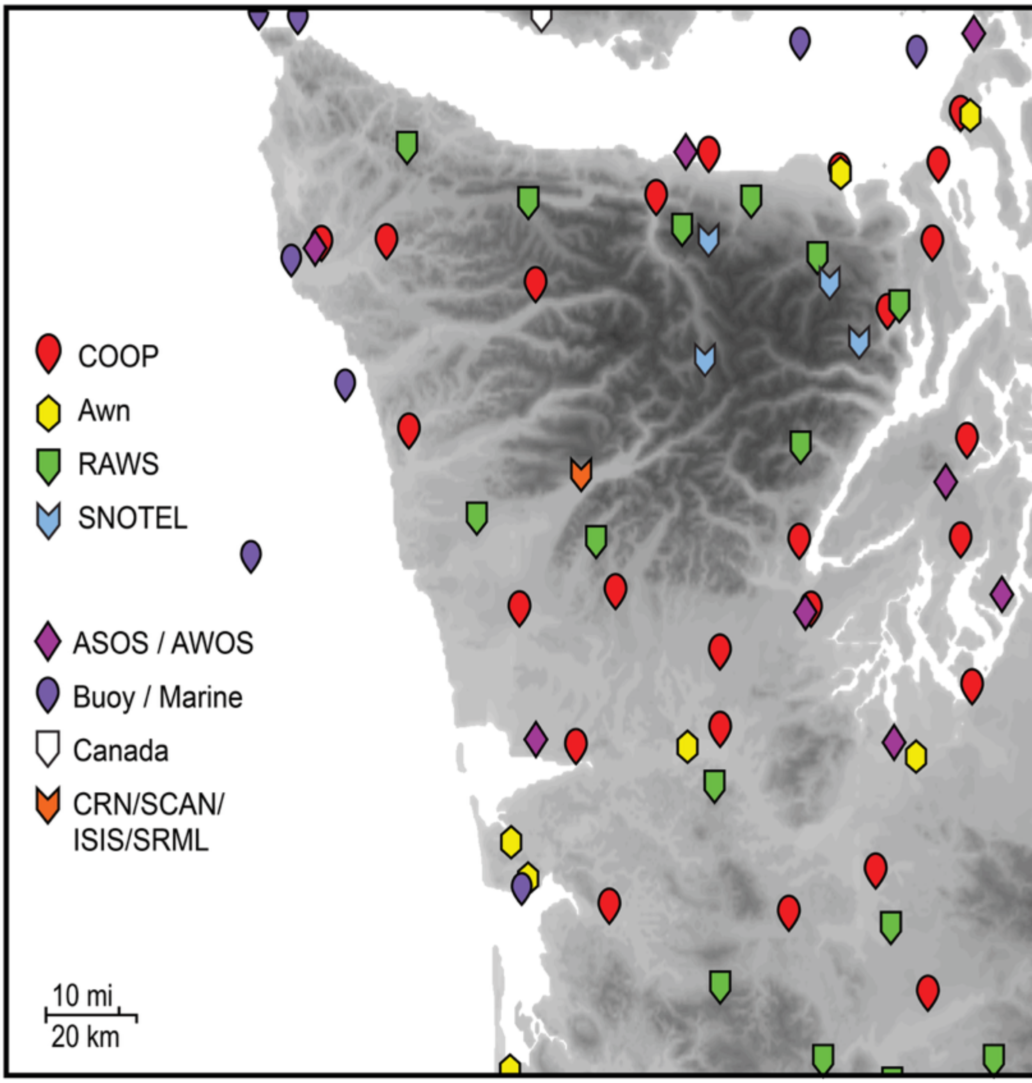


Figure 7: The existing network of surface observations in and around the Olympic Peninsula. ASOS, SNOTEL, RAWS, Buoy, CRN and Canadian sites all report various meteorological parameters hourly, the COOP sites report precipitation once a day.

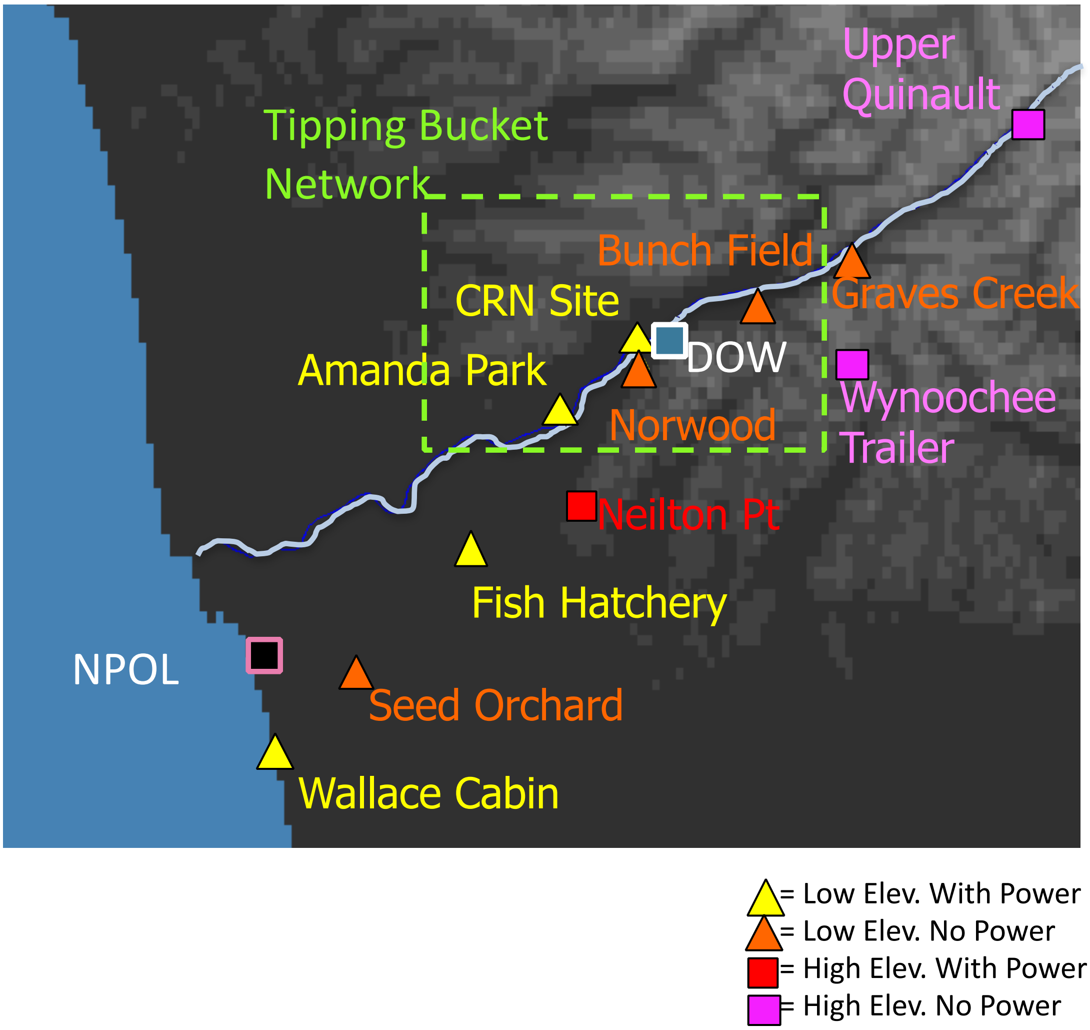


Figure 8: Locations of the surface network (triangles) and the NPOL and DOW radars (squares)that will be deployed for OLYMPEX. See Table 1 for the instruments to be installed at each site.

Figure 9: OLYMPEX Trailer instrumented with a Parsivel and Pluvio and powered by batteries and solar panel. It is currently deployed at Snoqualmie Pass.

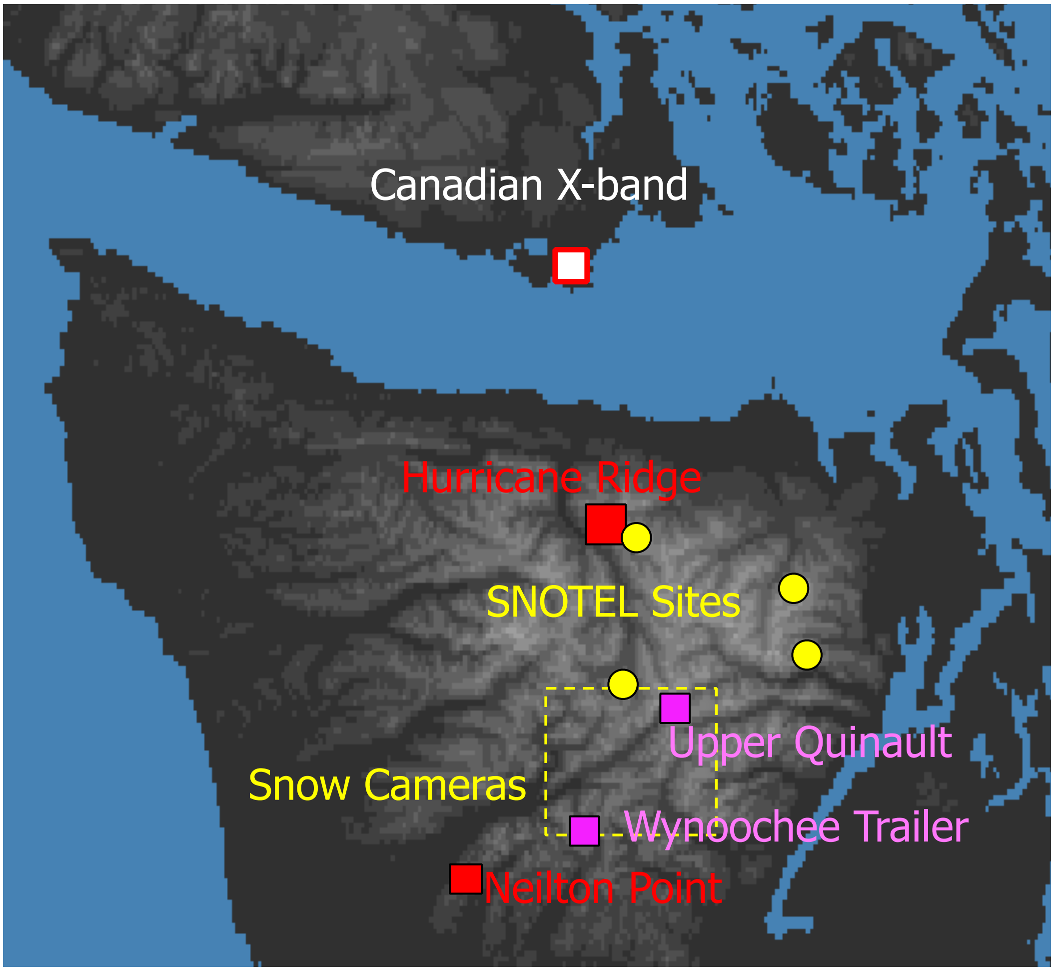


Figure 10: Locations of high terrain stations including SNOTEL, instruments at Hurricane Ridge, high elevation site Neilton Point and the remote sites of Enchanted Valley and the Wynoochee Trailer. The Canadian X-band is also shown for reference.

Figure 11: The suite of instruments installed at Hurricane Ridge on the north side of the Olympic Peninsula. They include a PIP, MRR, Parsivel and Hot Plate (not shown).

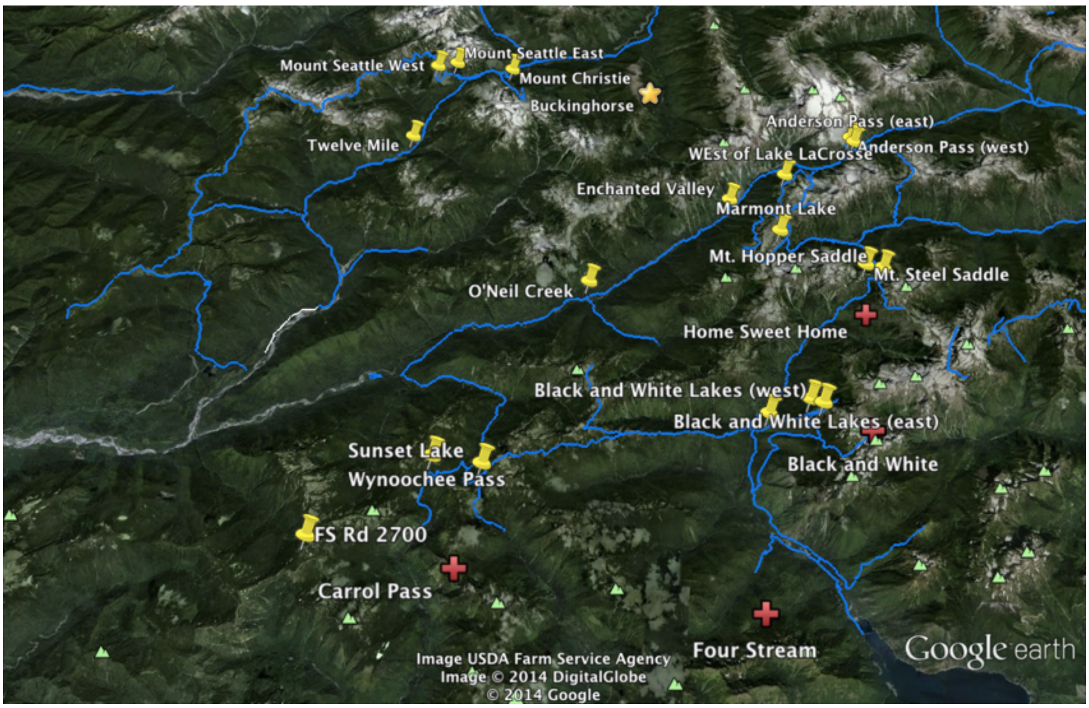


Figure 12: Locations of all the snow cameras installed for the 2014-2015 winter season.

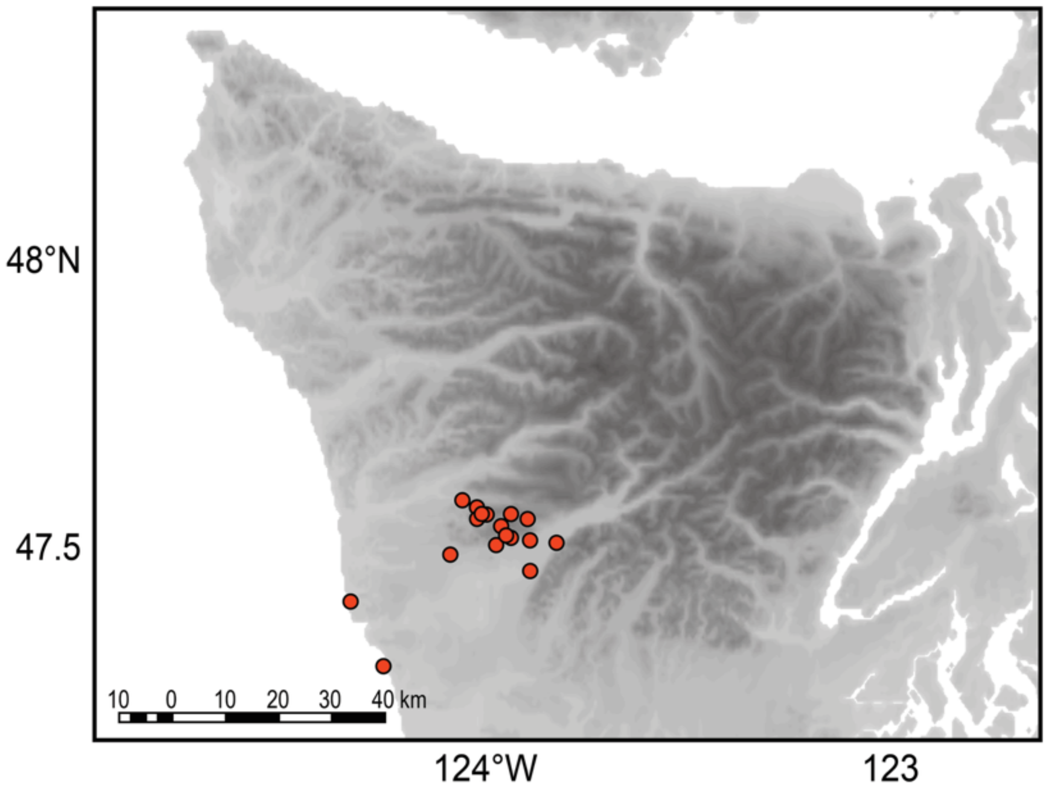


Figure 13: Locations of the UW tipping bucket rain gauge network.

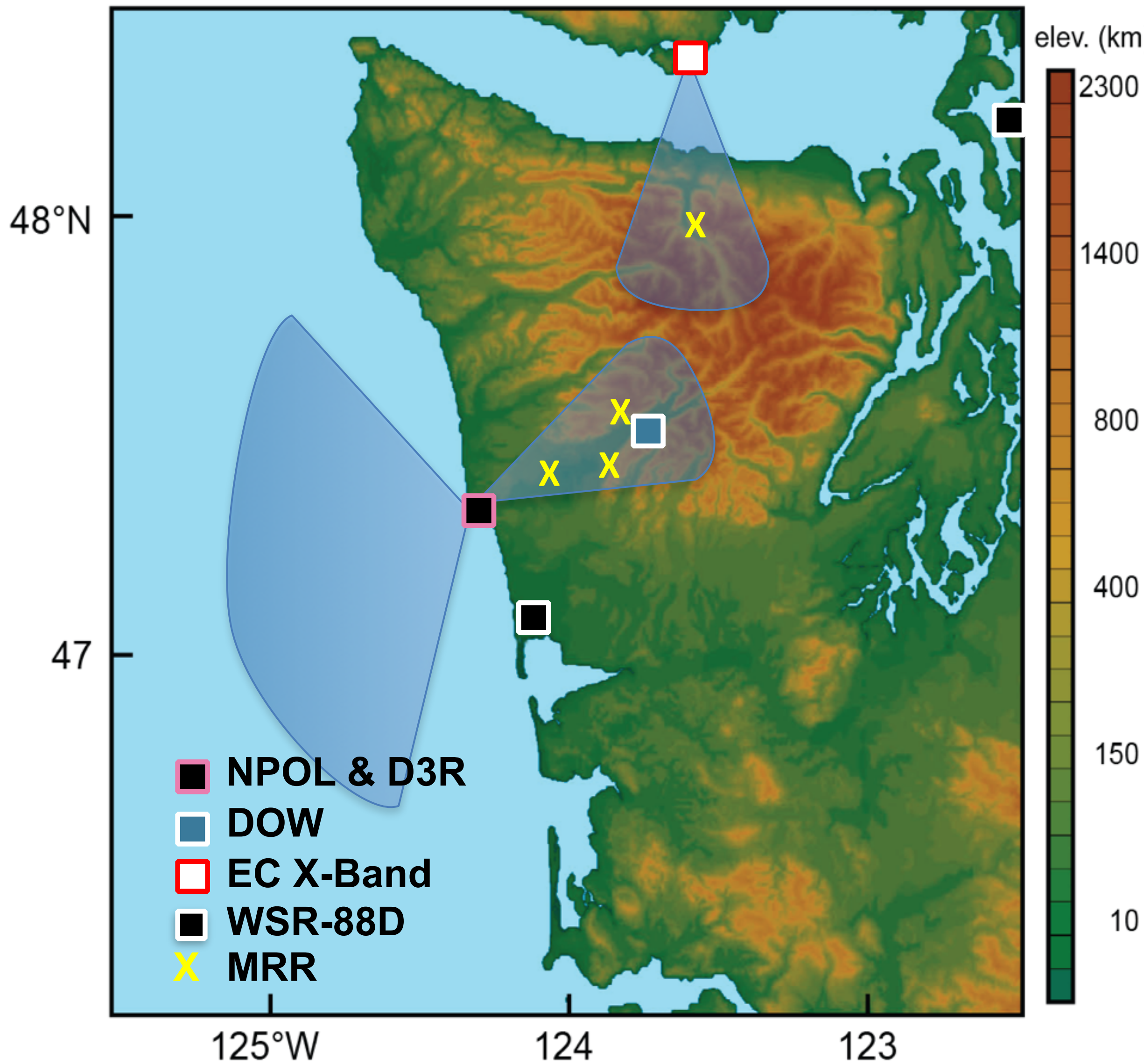


Figure 14: Locations of all the available ground radars for OLYMPEX and the RHI scanning regions for NPOL and EC X-band.

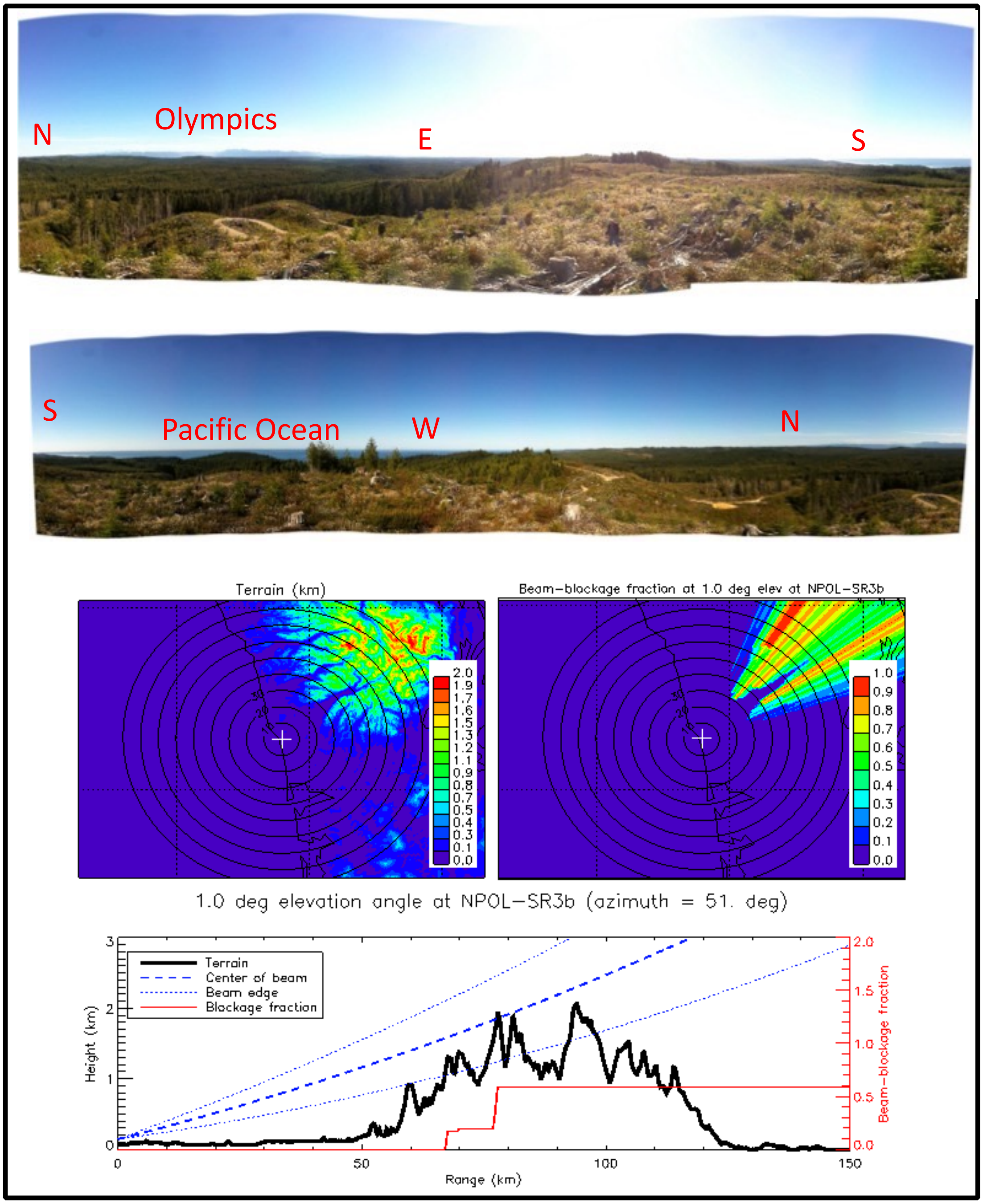


Figure 15: Panoramic views from the NPOL site (upper) and blockage estimates (lower). Note the clear view up the Quinault valley.

Figure 16 Reference Map

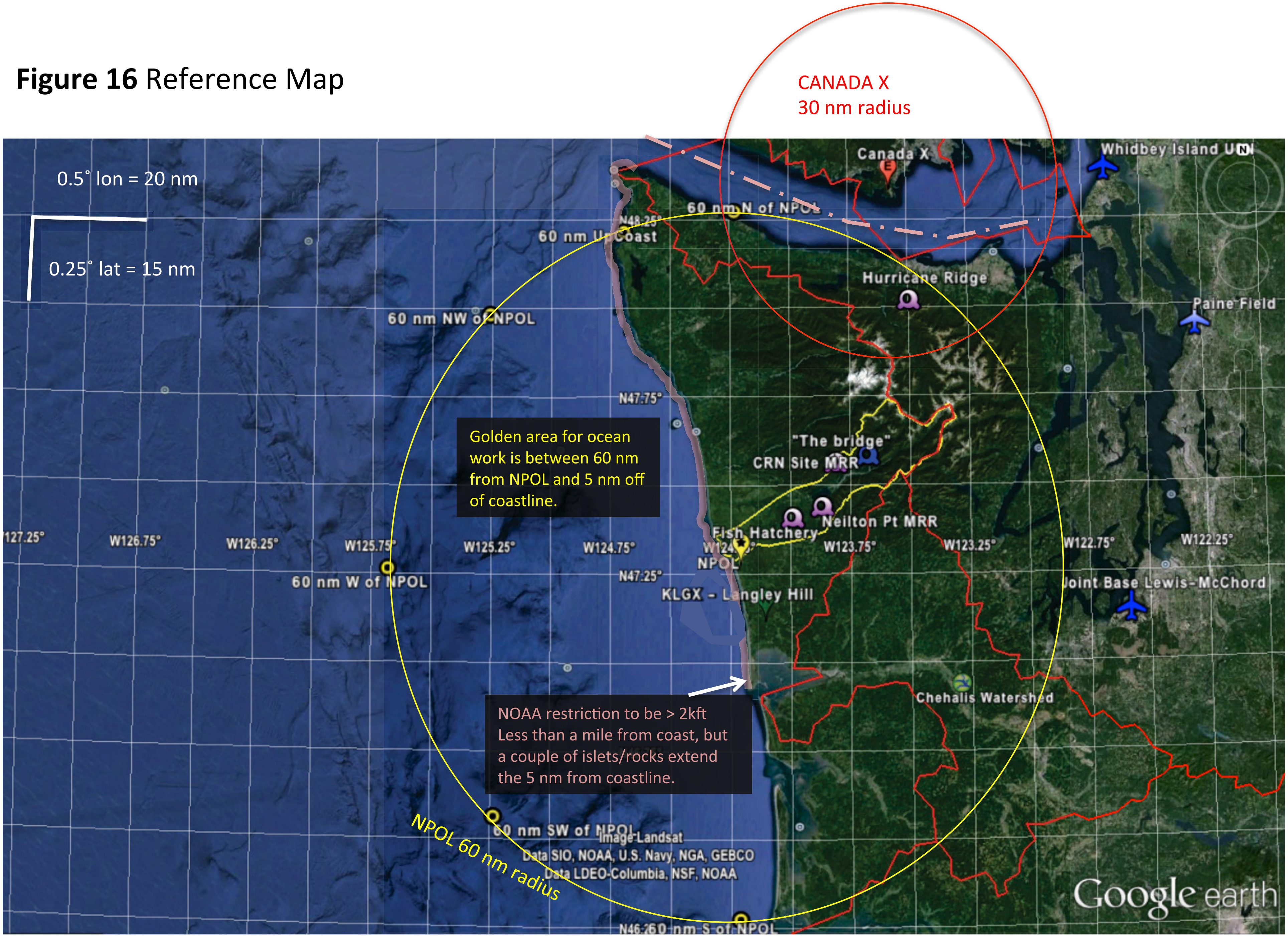


Figure 17 Calibration

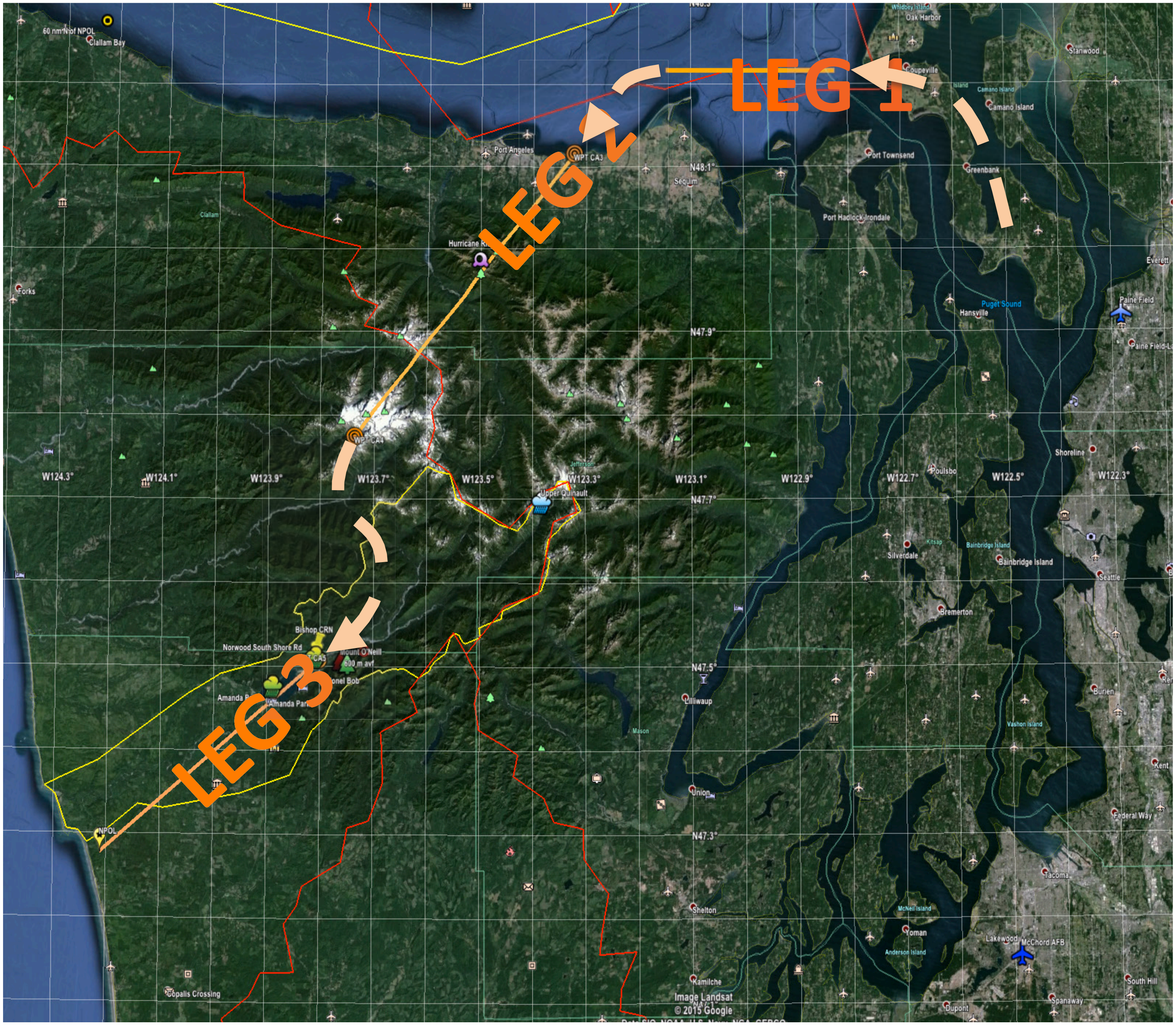
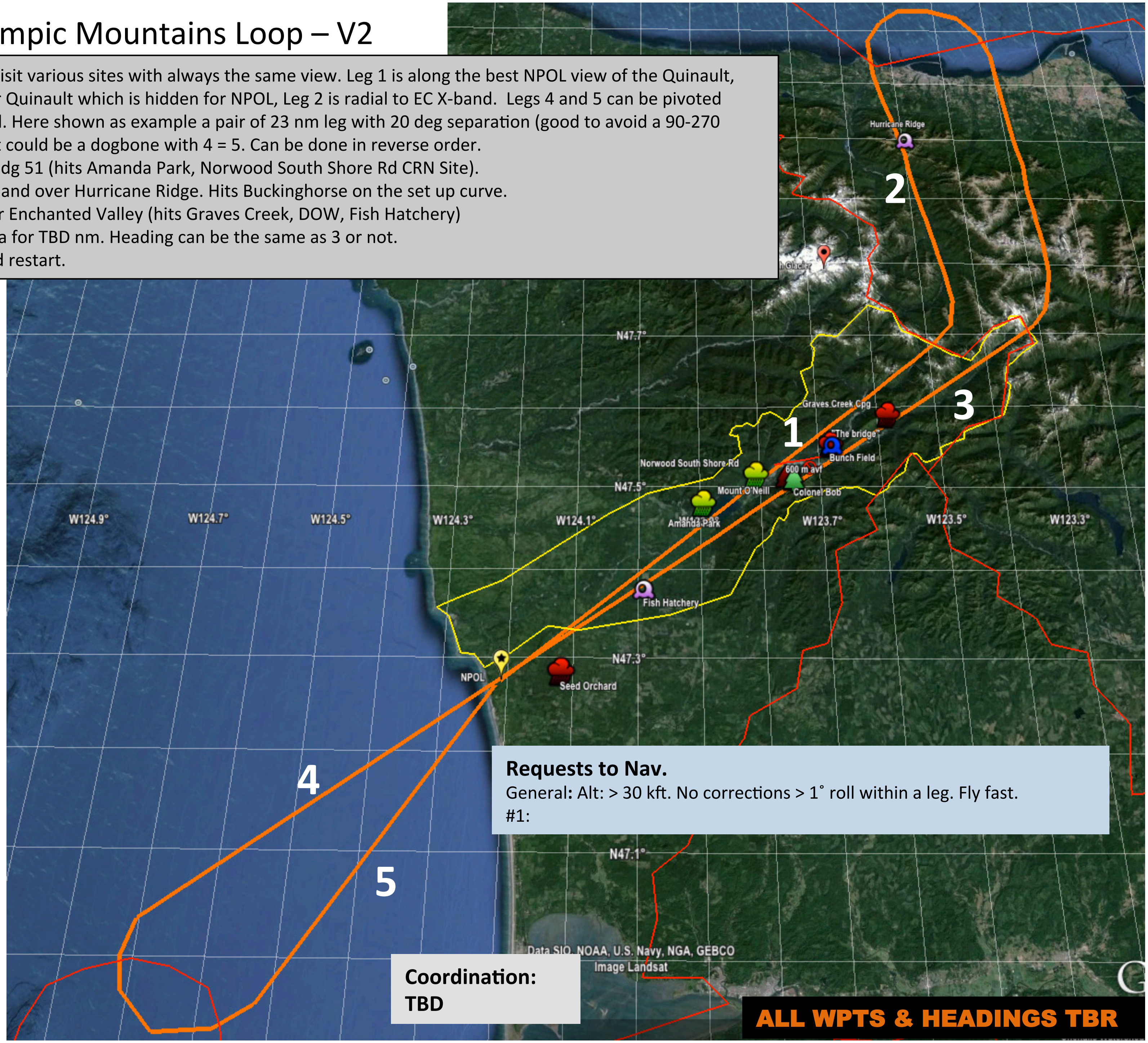


Figure 18 Olympic Mountains Loop – V2

Notes: Fixed loop to revisit various sites with always the same view. Leg 1 is along the best NPOL view of the Quinault, Leg 3 is along the Lower Quinault which is hidden for NPOL, Leg 2 is radial to EC X-band. Legs 4 and 5 can be pivoted around NPOL as needed. Here shown as example a pair of 23 nm leg with 20 deg separation (good to avoid a 90-270 which costs time), but it could be a dogbone with 4 = 5. Can be done in reverse order.

1) Radial from NPOL hdg 51 (hits Amanda Park, Norwood South Shore Rd CRN Site).
2) Radial to EC-Xband and over Hurricane Ridge. Hits Buckinghorse on the set up curve.
3) Radial to NPOL over Enchanted Valley (hits Graves Creek, DOW, Fish Hatchery)
4) Extension out to sea for TBD nm. Heading can be the same as 3 or not.
5) Return to NPOL and restart.



Requests to Nav.
General: Alt: > 30 kft. No corrections > 1˚ roll within a leg. Fly fast.
#1:

Shown length:
250 nm
(~34 min)

Coordination:
TBD

Figure 19 NPOL Loop – V1 (Applies to: DC-8, ER-2)

Notes: Fixed loop to revisit the Quinault and the Ocean Sector in front of it. Leg 1 is the same as Olympus Loop, Leg 2 is same as Olympus Leg 3. Can be done in reverse order direction

1) Radial from NPOL hdg 51 (hits Amanda Park, Norwood South Shore Rd CRN Site).
2) Radial to NPOL over Enchanted Valley (hits Graves Creek, DOW, Fish Hatchery)
3) Radial from NPOL at similar heading as Leg 2. Length and heading to be decided based on weather. The one shown goes all the way past Cliff's 100 km from the coast to capture orographic enhancement extent.
4) Radial to NPOL at similar heading as Leg 1, but also this one can be decided based on weather.

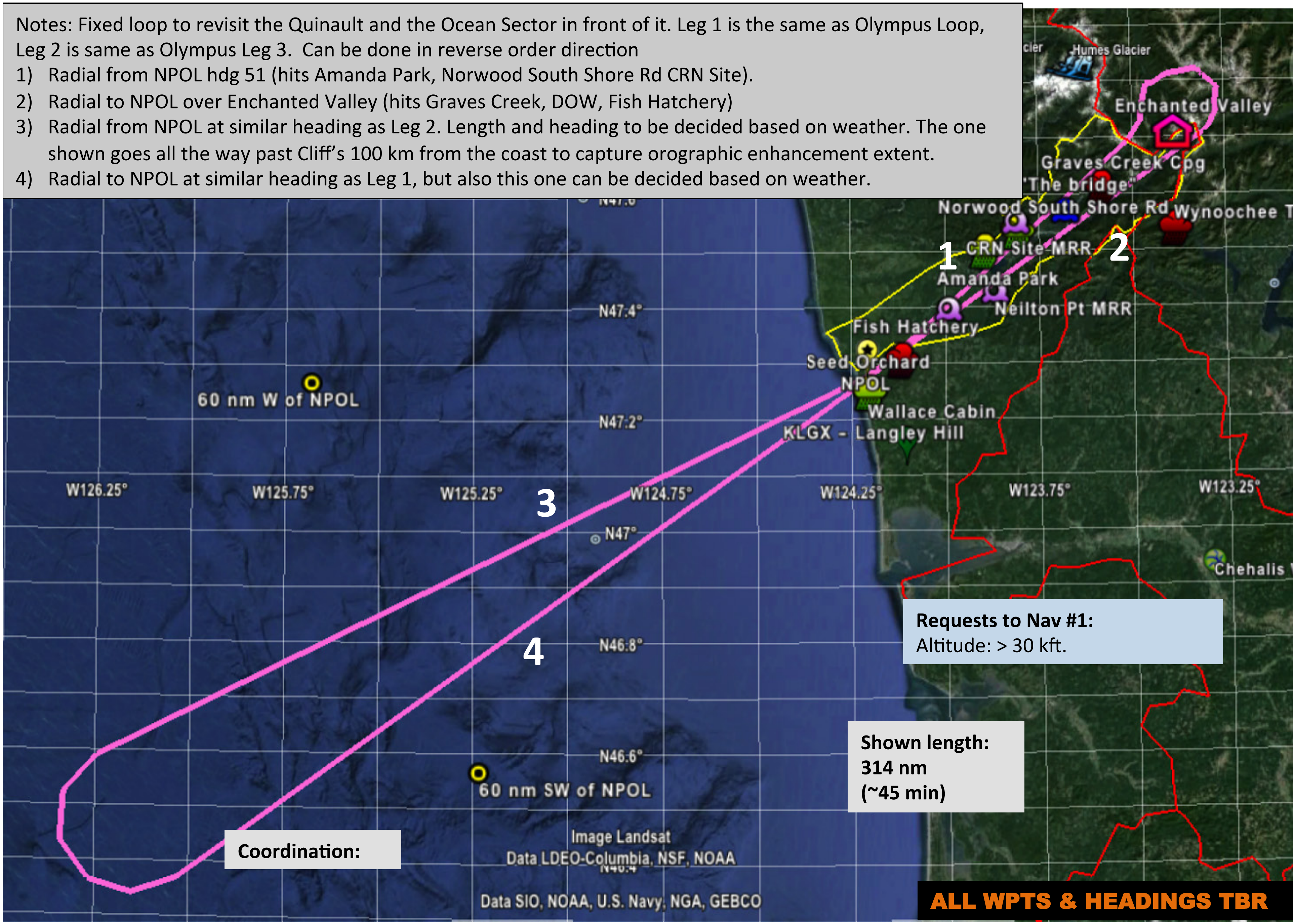


Figure 20 Snow Loop – V1 (Applies to: DC-8, ER-2)

Notes: Fixed loop to revisit most of the the Snow Sites. It misses one of the 3 (Sunset Lake). Possible variant to hit it is dashed (not true to aircraft radii). To be refined with Jessica.

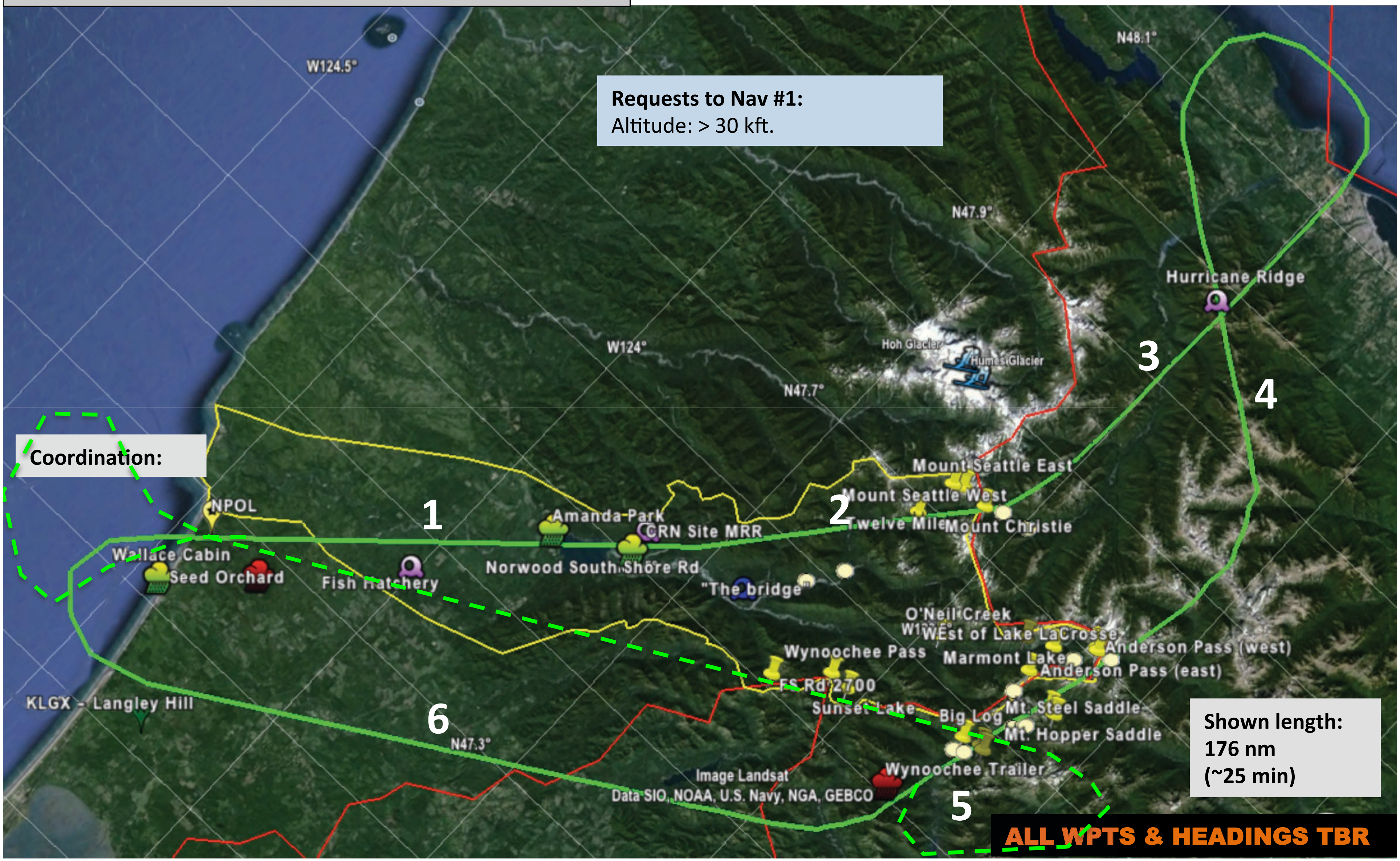


Figure 21 Chehalis Loop – V1 (Applies to: DC-8, ER-2)

Notes: Fixed loop to cover the Chehalis in case major precip is forecasted over the Chehalis. Essentially two racetracks that criss cross in the SW portion of the basin that according to Cliff was culprit of last flood. One branch covers raingages and KLGX blind corner in the N of the basin, the other branch covers the flow from SW on the region of major orographic enhancement.

NORTH

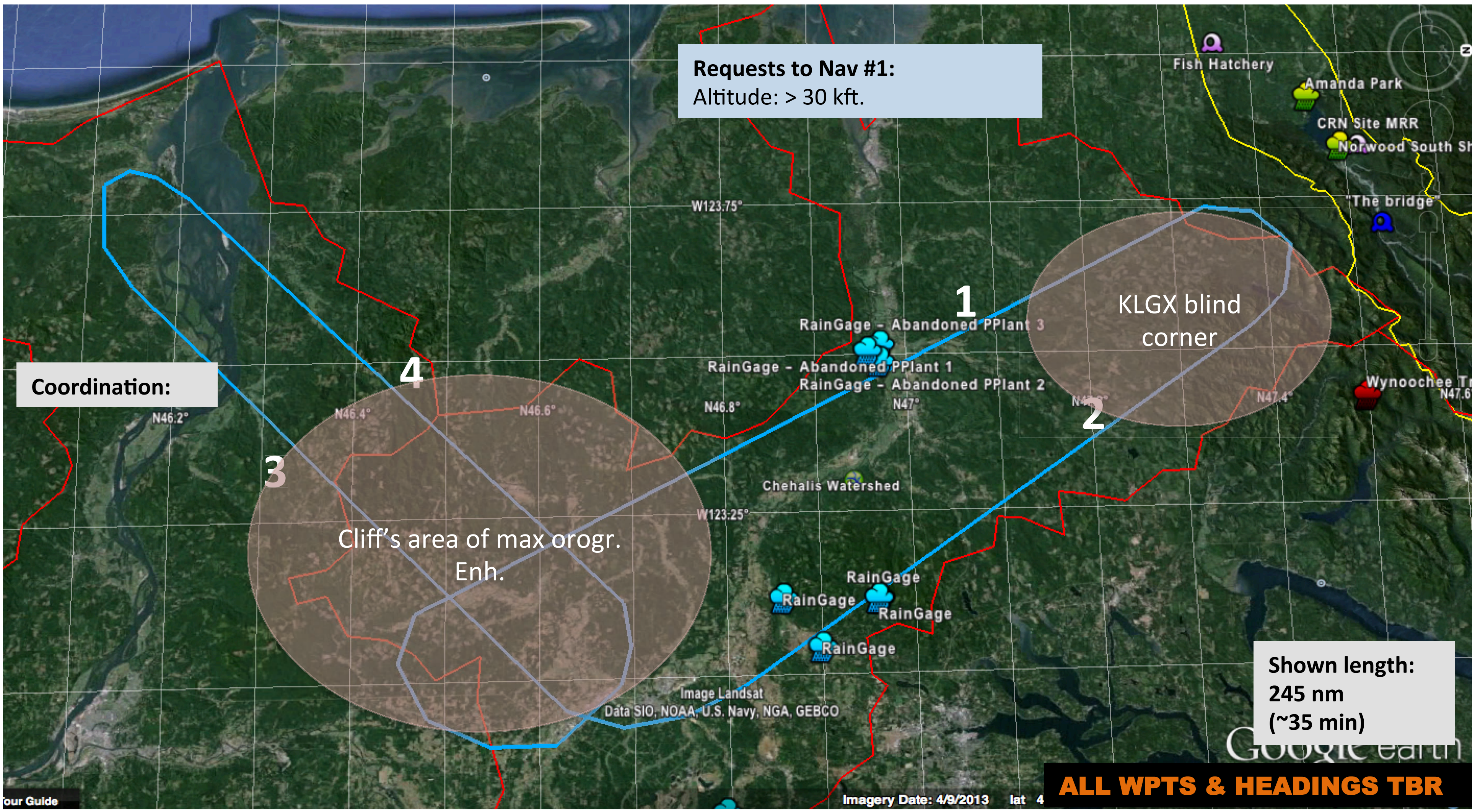


Figure 22a Narrow Racetrack– V1 (Applies to: DC-8, ER-2) (Example #1)

NOTE: THIS IS A MOVABLE MODULE, THE LOCATION SHOWN HERE IS JUST TO PROVIDE SOME SENSE OF SCALE AND HELP SIZING IT, IT COULD BE ANYWHERE. Defined by one waypoint (sliding), one heading (changeable, but better not), the leg length (here shown 20 nm as example), and the instruction to turn (to the left or right) in as tight of a turn as possible. This will exceed the APR-3 scan angle, so no good data in the curves, lidar on ER-2 needs to be shuttered in the turns. DC-8 and ER-2 to attempt simultaneity on main leg (Leg 1). Shown in green also a citation making a parking garage (level on the main leg, climb/descend on the other).

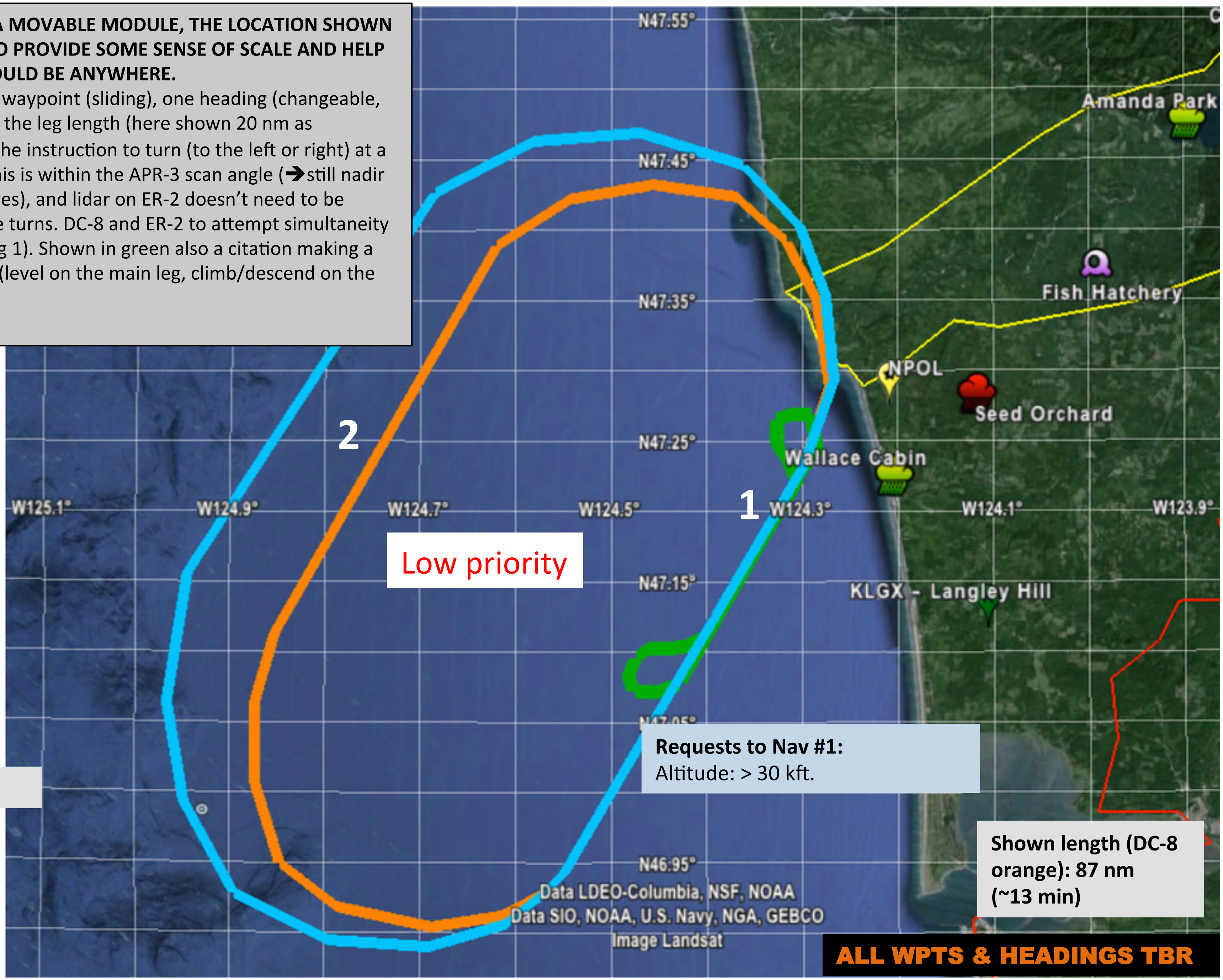
Requests to Nav #1:
Altitude: > 30 kft.

Shown length (DC-8 orange): 65 nm (~10 min)

Figure 22b Twenty Degree Racetrack– V1 (Applies to: DC-8, ER-2)

NOTE: THIS IS A MOVABLE MODULE, THE LOCATION SHOWN HERE IS JUST TO PROVIDE SOME SENSE OF SCALE AND HELP SIZING IT, IT COULD BE ANYWHERE.
Defined by one waypoint (sliding), one heading (changeable, but better not), the leg length (here shown 20 nm as example), and the instruction to turn (to the left or right) at a 20 deg bank. This is within the APR-3 scan angle (➔still nadir data in the curves), and lidar on ER-2 doesn't need to be shuttered in the turns. DC-8 and ER-2 to attempt simultaneity on main leg (Leg 1). Shown in green also a citation making a parking garage (level on the main leg, climb/descend on the other).

1) Yatta yatta



Coordination:

Requests to Nav #1:
Altitude: > 30 kft.

Shown length (DC-8 orange): 87 nm (~13 min)

ALL WPTS & HEADINGS TBR

Figure 23 Movable Racetracks – Do it yourself (hi tech version)

Each racetrack is designated by: LEG LENGTH (nm) / RADIUS OF TURN (nm) ~ Time to execute at 400 kts. Everything is approx.

Four samples are provided for starters, two narrow and two 20deg banks (3.5 nm is for the narrow racetrack and 6 is for the 20 deg bank).

20 and 40 nm long legs. Stretch only **width** to adjust **leg length**. Shift and rotate at will.

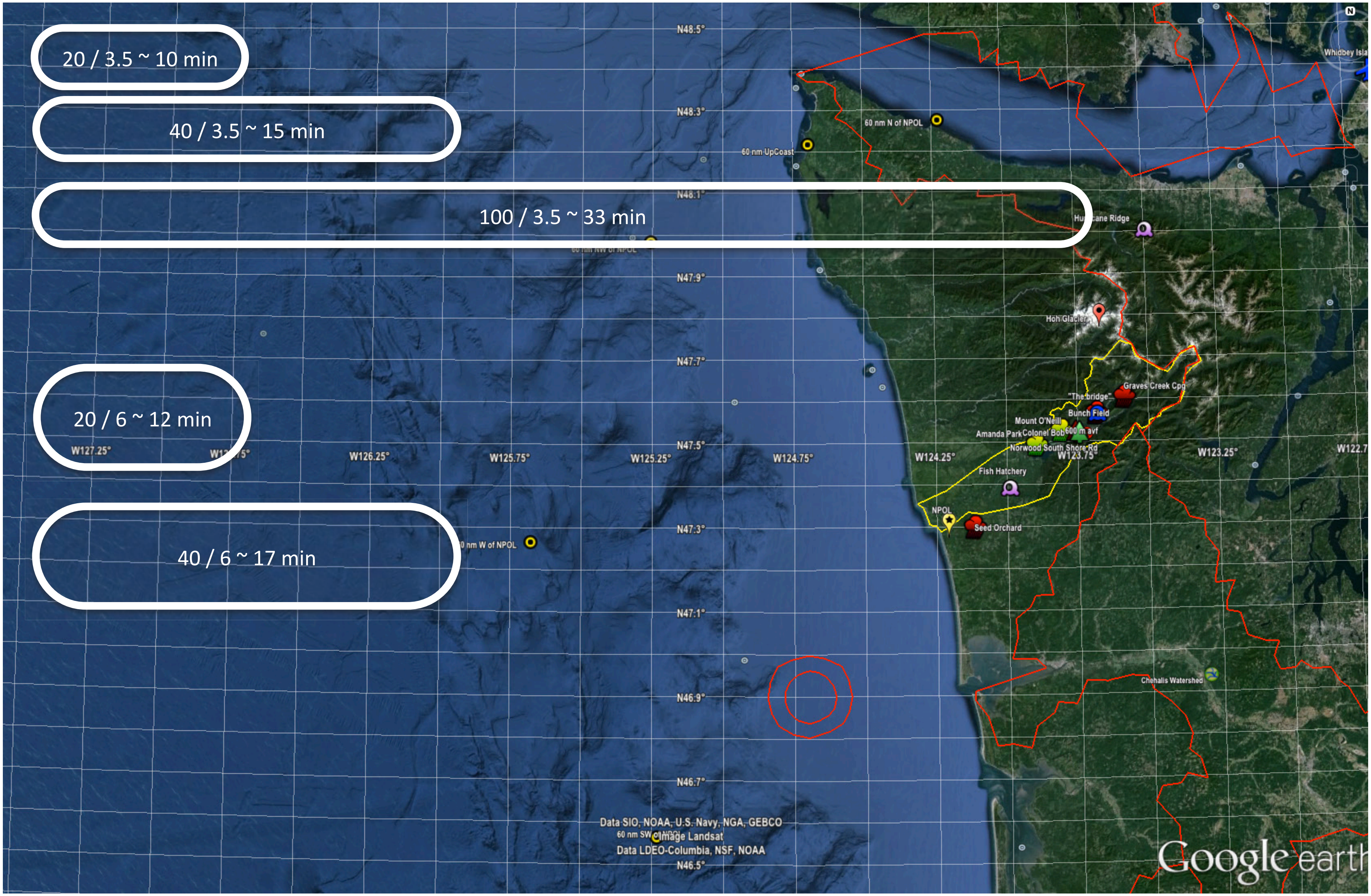


Figure 24 Wide Survey – V1 (Applies to: DC-8, ER-2)

Defined by 5 waypoints, one usually NPOL. Dropsoundings at any time other than in the 10 min before a turn or during a turn. Not designed as a loop because won't be repeated consecutively.

1) Yatta yatta

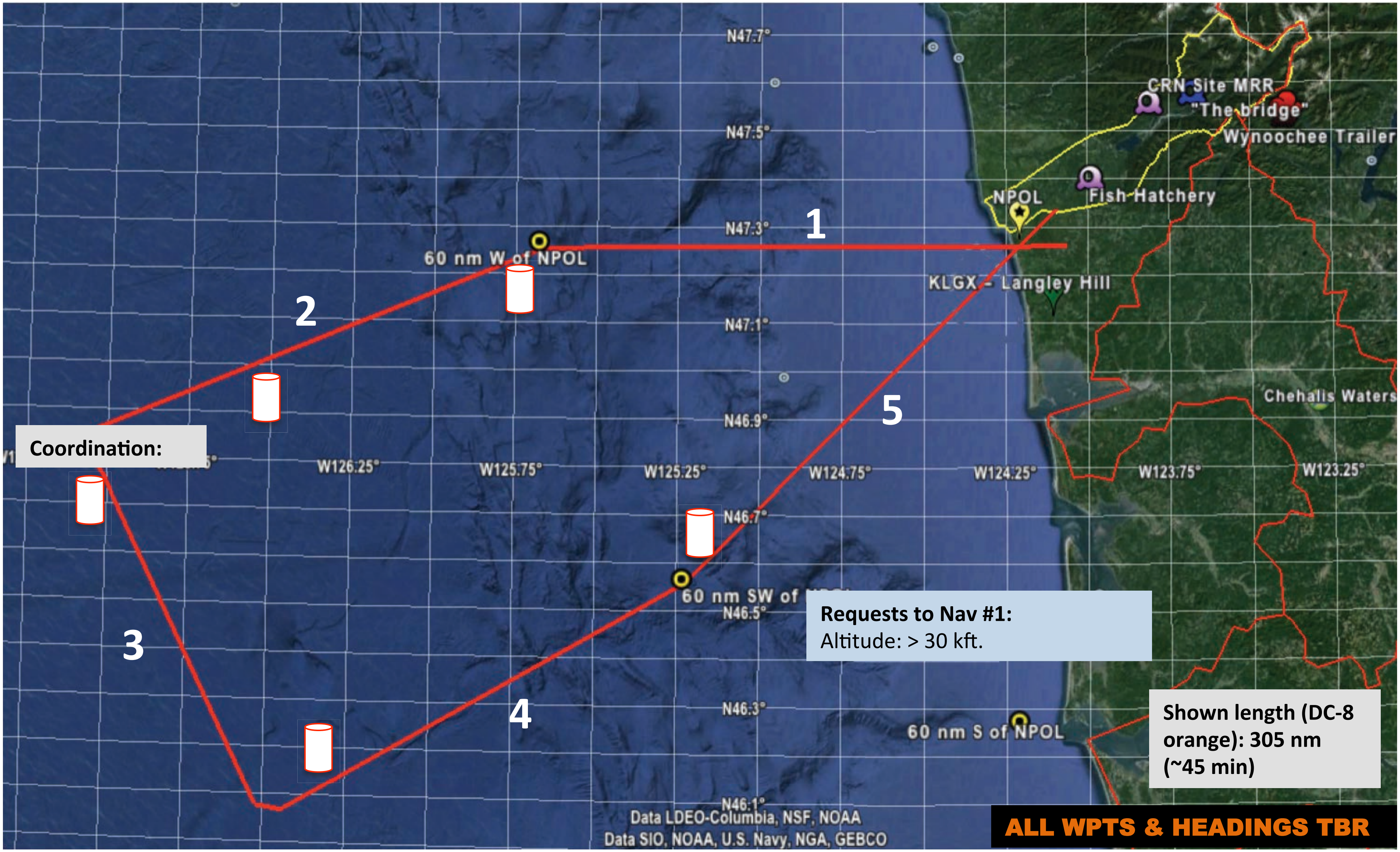


Figure 25 Wide ZigZag– V1 (Applies to: DC-8, ER-2)

Defined by 7 waypoints, one usually NPOL. Dropsoundings at any time other than in the 10 min before a turn or during a turn. Not designed as a loop because won't be repeated consecutively.

1) Yatta yatta

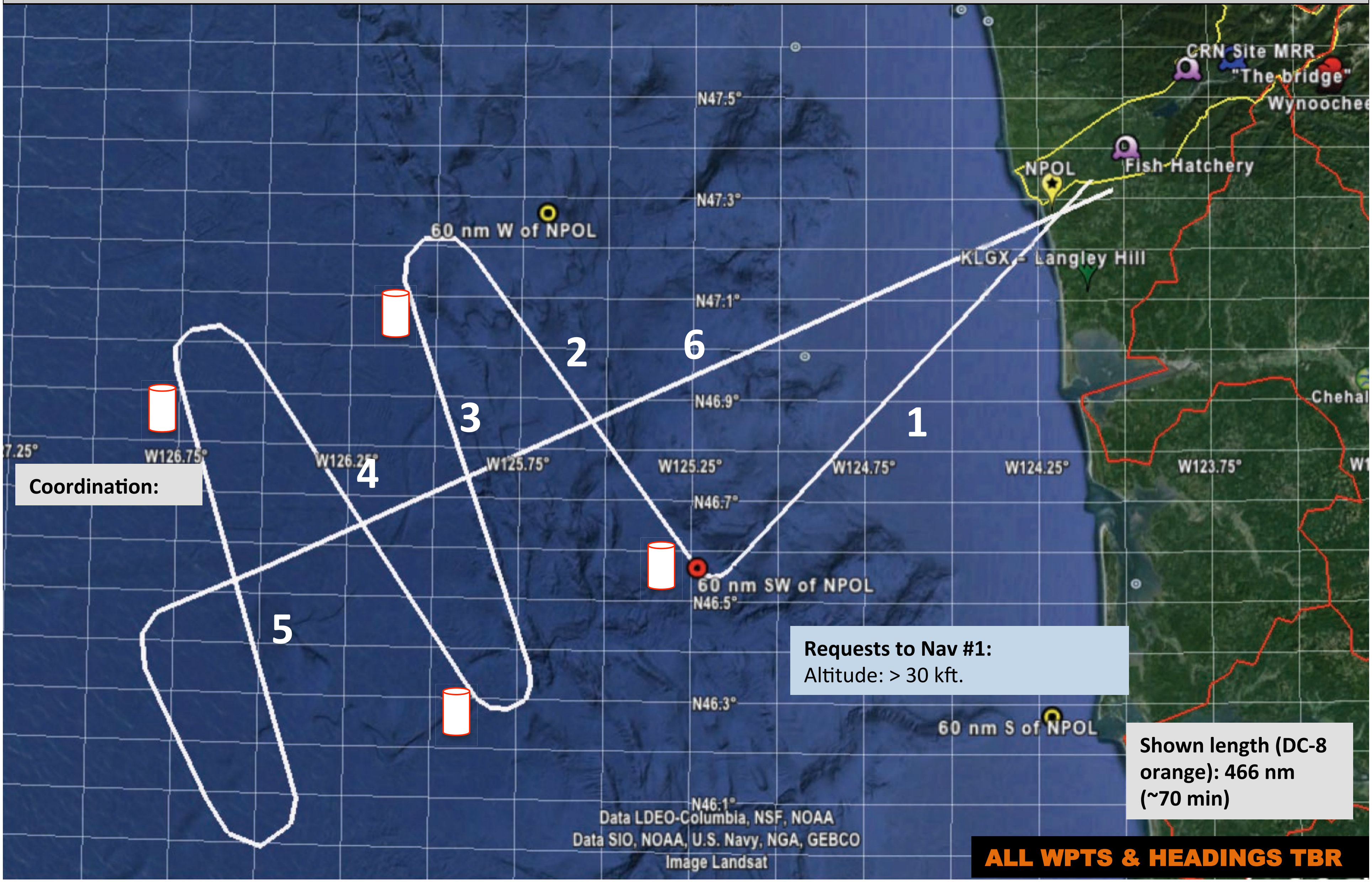


Figure 26a GPM overpass – Ascending Ocean, Shown: Ka-DPR swath
Assume: front is out over ocean inside the swath.
Possible module: cut across the swath twice for surface clutter removal validation.

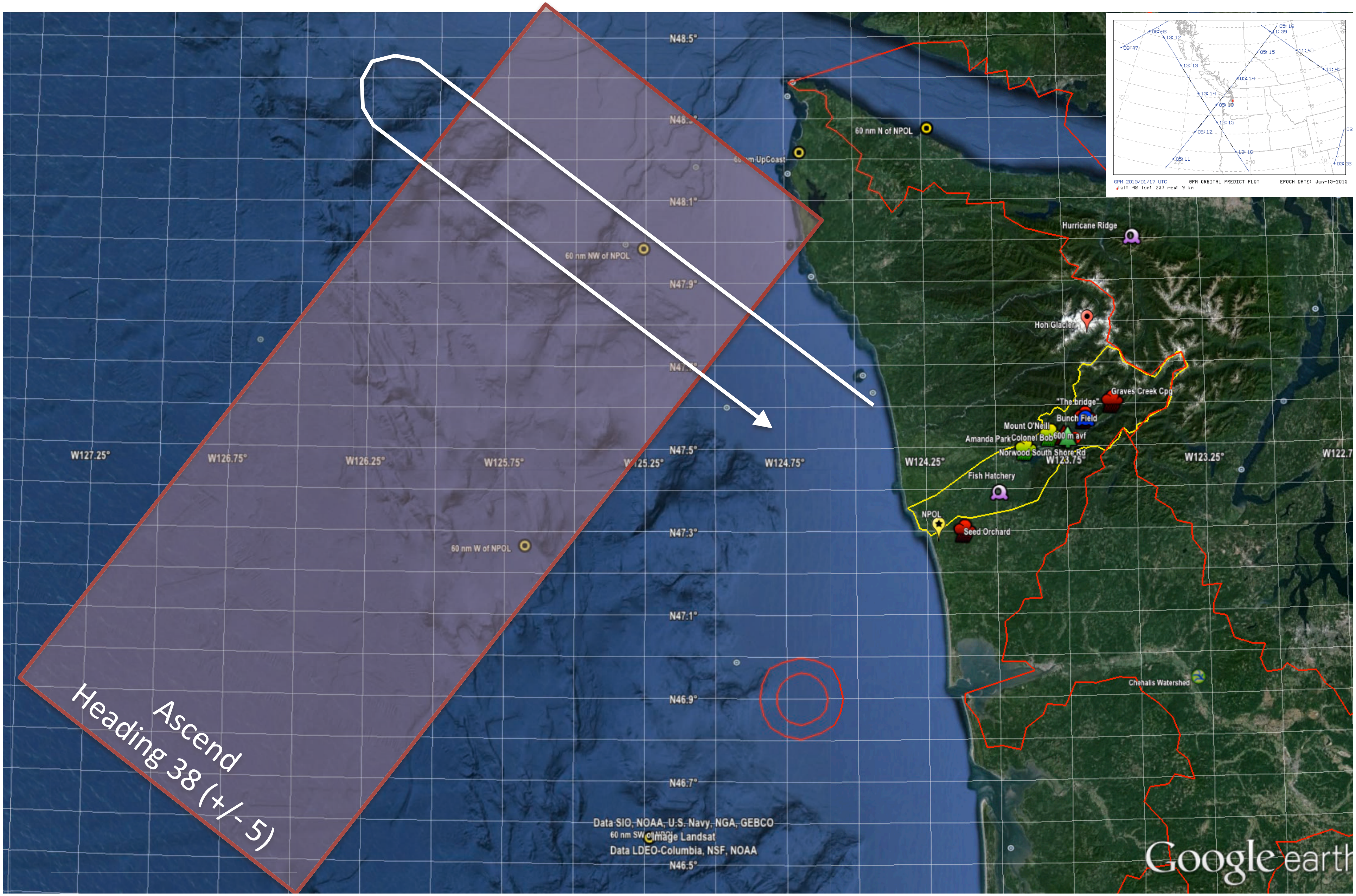


Figure 26b GPM overpass – Ascending Land, Shown: Ka-DPR swath

Assumption: post frontal on the slopes of Olympus. Westerly flow.

Possible module: fly along a well exposed valley which has the windward side either at nadir or the starboard of GPM (better illumination)

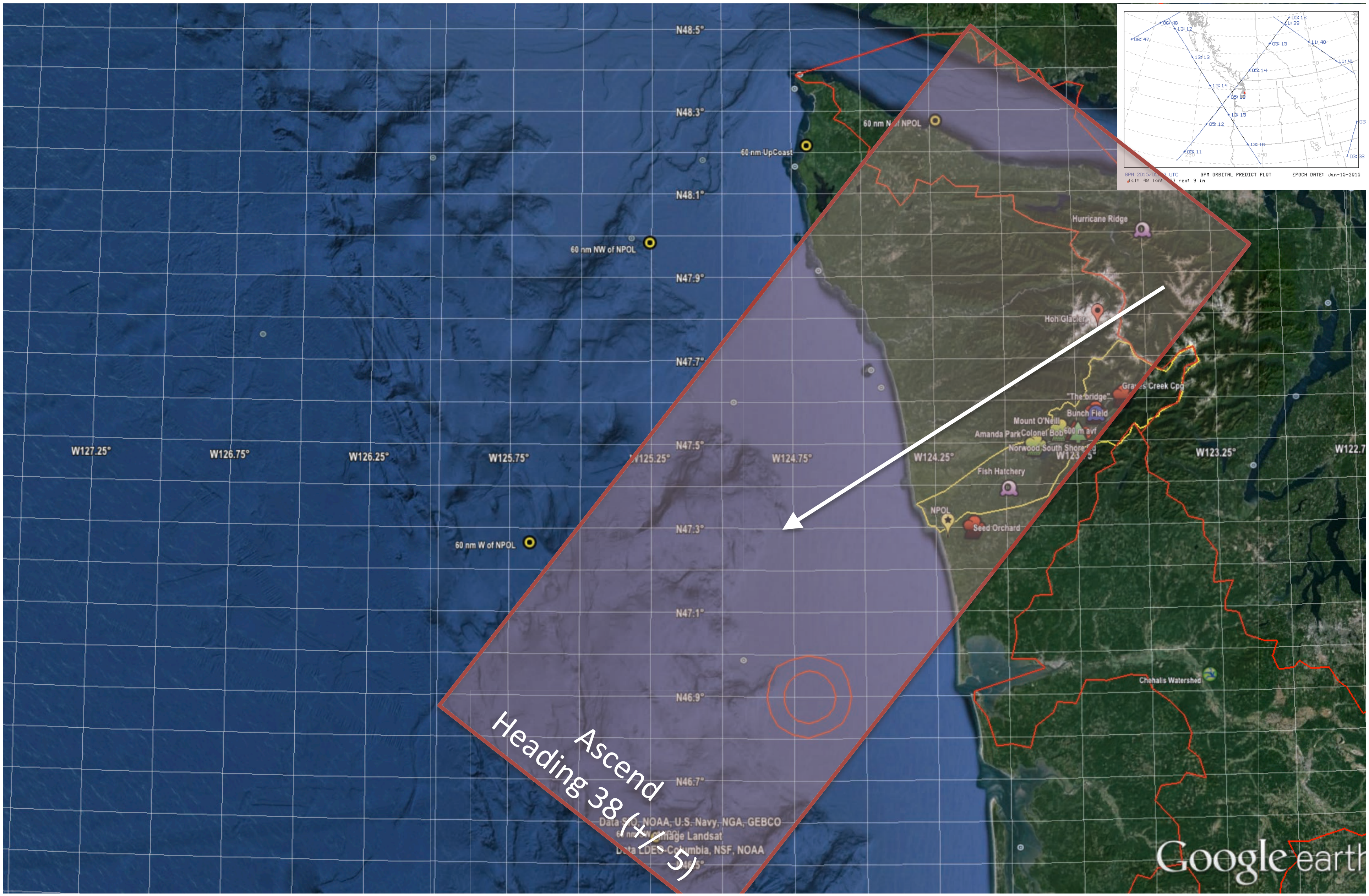


Figure 26c GPM overpass – Descending Ocean, Shown: Ka-DPR swath
Assumption: prefrontal right off the coast from NPOL.
Possible module: fly out of NPOL radial and cut across. Both L2 product and surface clutter validation.

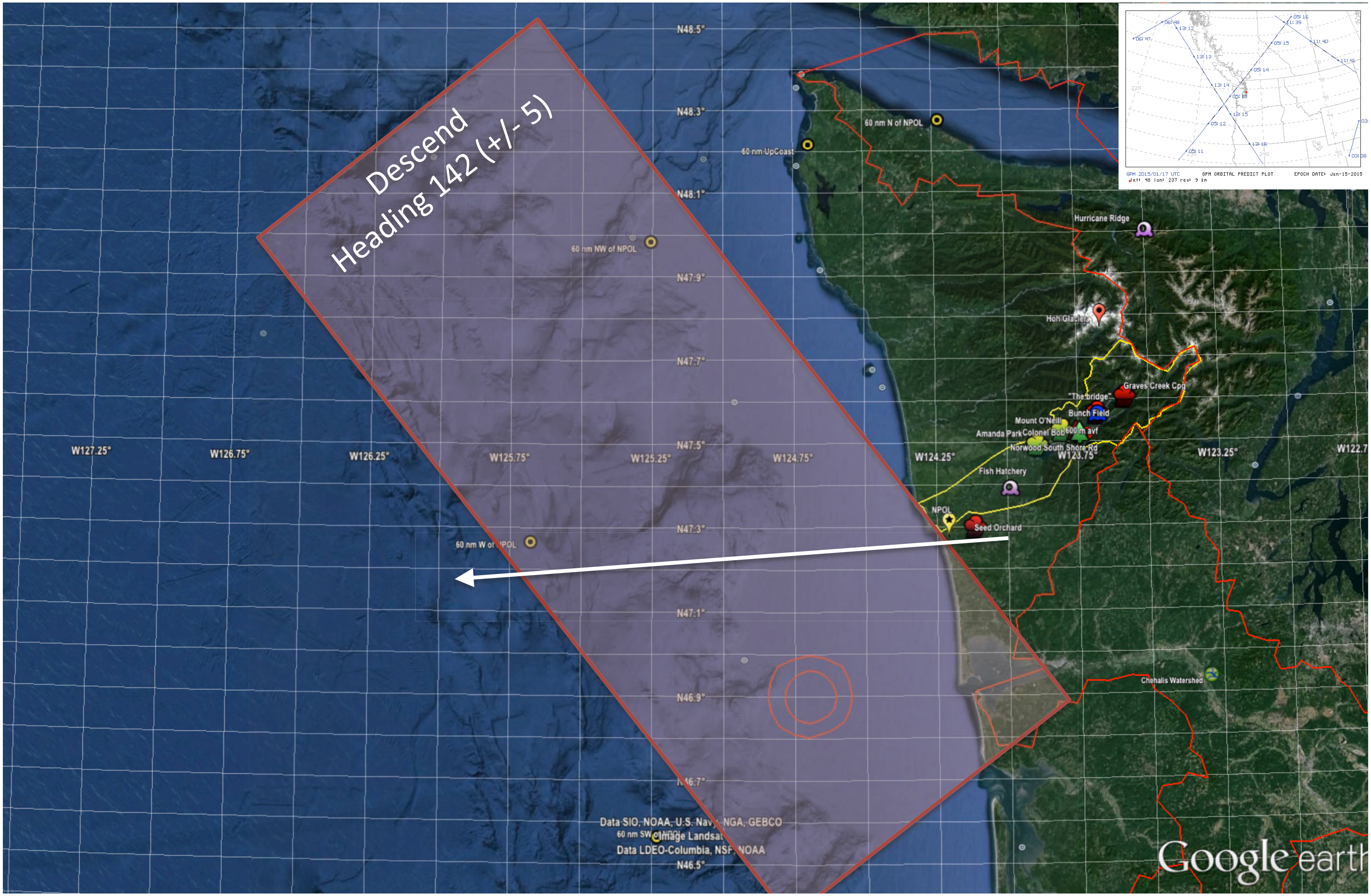


Figure 26d GPM overpass – Descending Land, Shown: Ka-DPR swath
Assumption: almost clear
Possible module: fly along track to calibrate radiometers and radar.

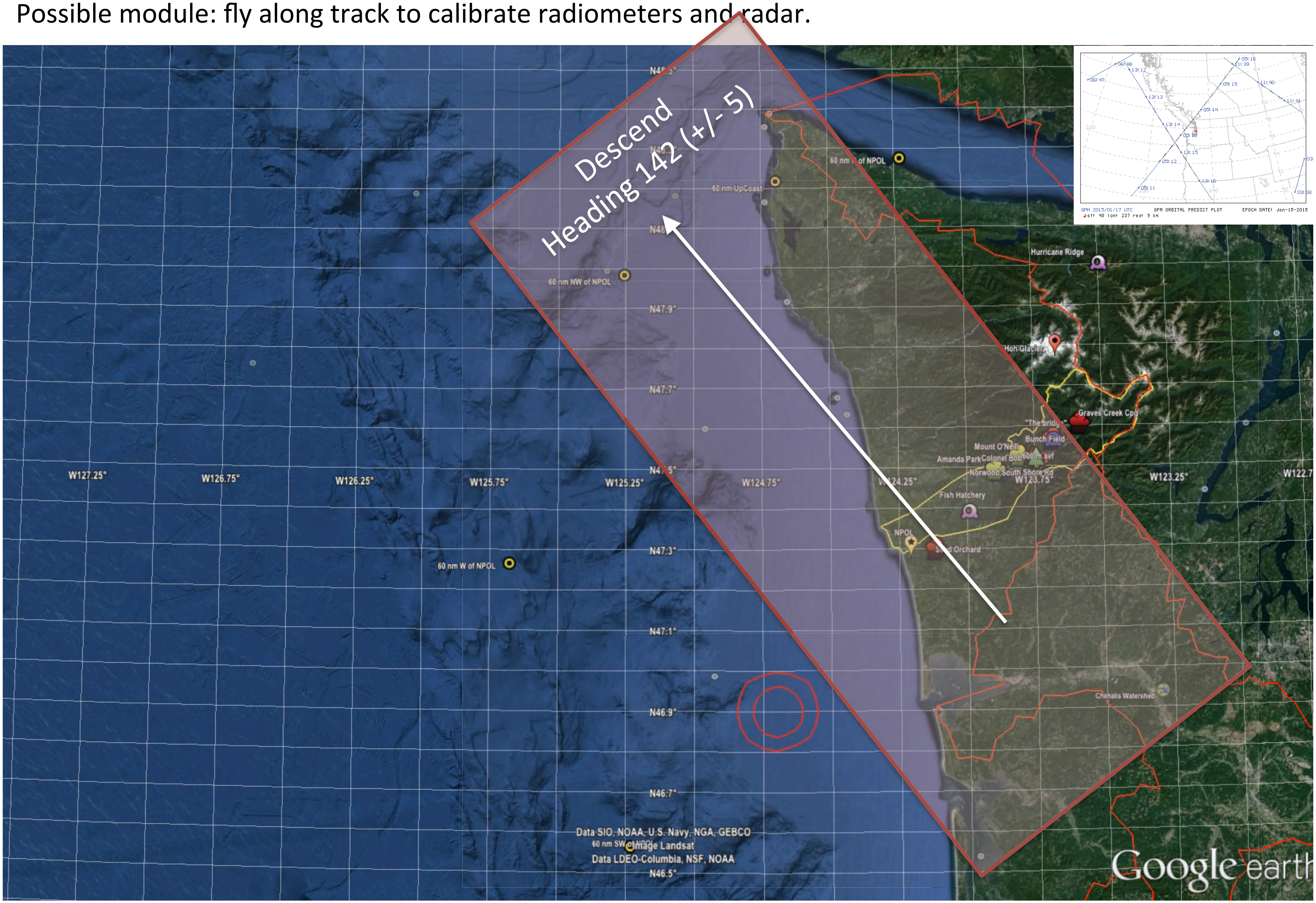
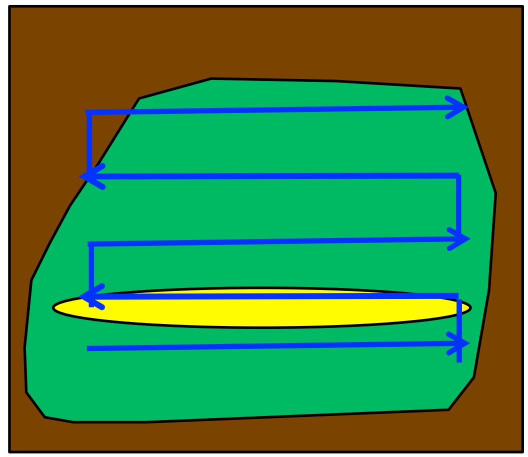


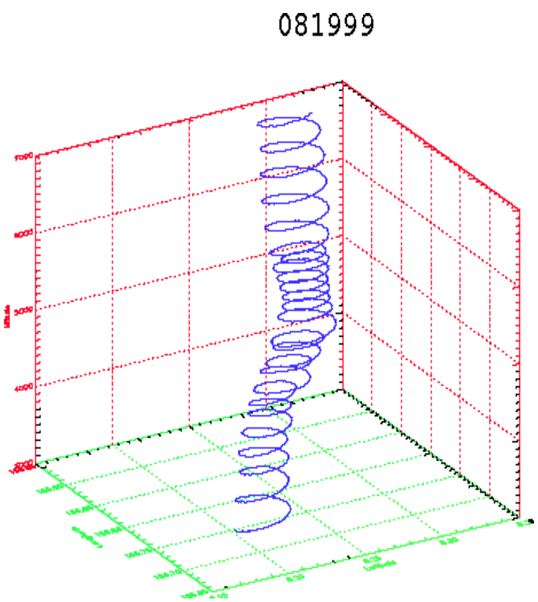
Figure 27 Citation flight patterns for microphysical sampling

(a) Step Climb/Descent



5 levels, 40 nm legs (3 min/10 nm)
2000’ interval (2 min/climb & turn)
= 70 minutes (nominal)

(b) Lagrangian Spiral



-10°C to 0°C @200 fpm
0°C to +5°C @300 fpm
= 40 minutes (nominal)