Jet Propulsion Laboratory
California Institute of Technology

AUTOMATED DATA PRODUCTION FOR A NOVEL AIRBORNE MULTIANGLE SPECTROPOLARIMETRIC IMAGER (AIRMSPI)

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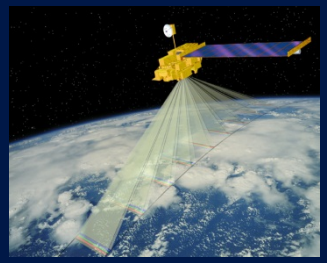
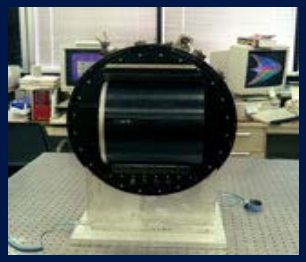
Outline

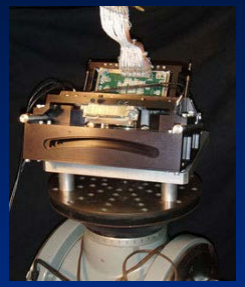
Multi-angle Measurements Evolution at JPL



MISR (Multi-angle Imaging SpectroRadiometer) flying on board NASA Terra platform since 2000. Nine discreet view angle with four spectral band in each. Data at NASA Langley DAAC.



AirMISR single gimbaled camera flew on NASA' s ER-2 aircraft. In operation for seven years until September of 2004. Supported variety of MISR and other scientific campaigns in North America and southern Africa. Data at NASA Langley DAAC



GroundMSPI (Ground Multiangle SpectroPolarimetric Imager) operating at the University of Arizona's College of Optical Sciences. Nine spectral bands. Three of them are polarimetric.

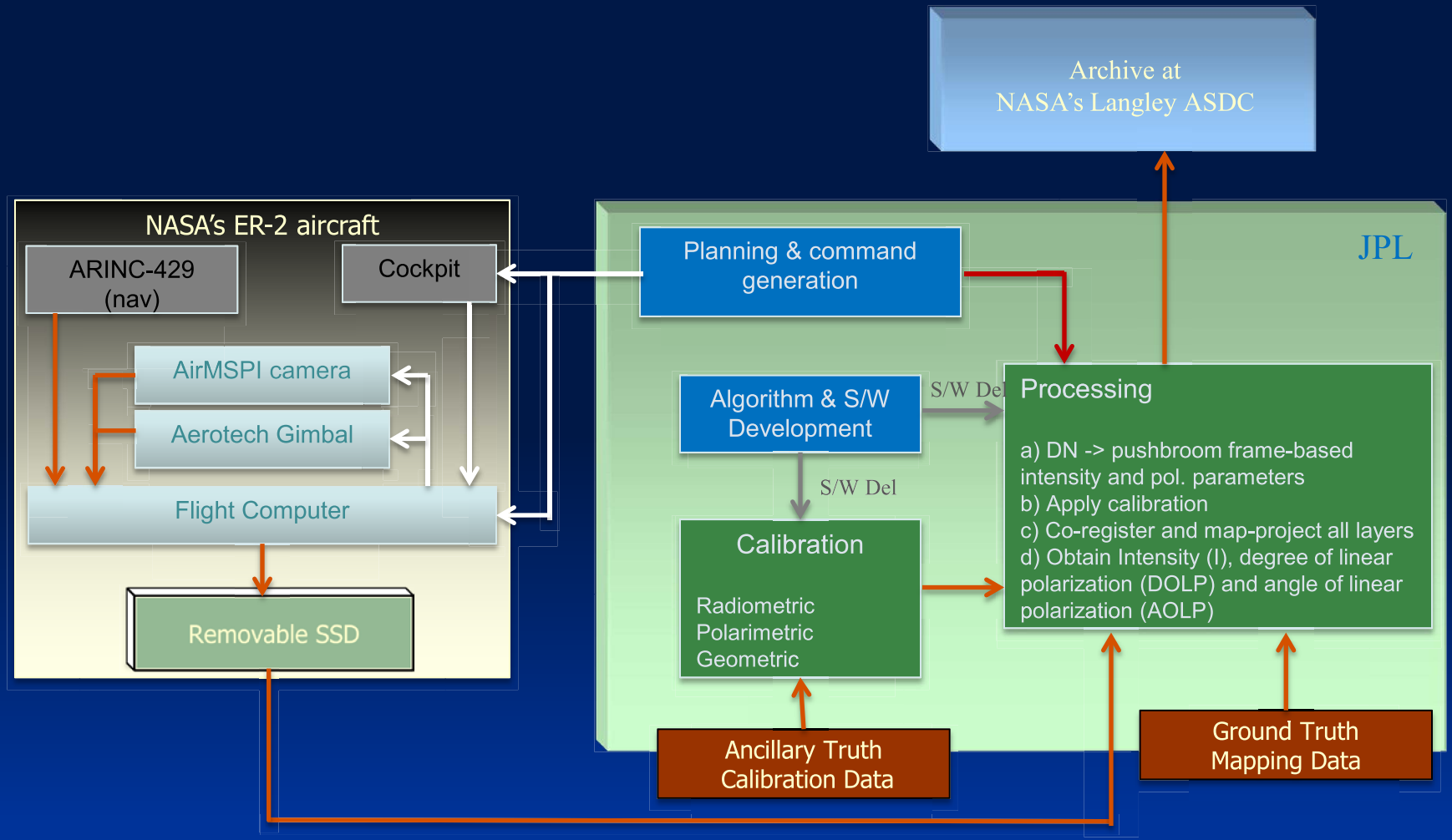
AirMSPI (Airborne Multiangle SpectroPolarimetric Imager) operating at the JPL and flying on NASA's ER-2 aircraft. Single gimbaled camera. Nine spectral bands. Three of them are polarimetric.

From MISR to MSPI

Capability	Multi-angle Imaging SpectroRadiometer (MISR)	Airborne Multiangle SpectroPolarimetric Imager (AirMSPI) current config.	Multiangle SpectroPolarimetric Imager (MSPI) strawman concept
UV bands	Not included	365, 385 nm	365, 385 nm
VNIR bands	446, 558, 672, 866 nm	445*, 540, 645*, 762.5, 865* nm *polarimetric bands	445*, 540, 645*, 762.5, 865* nm
SWIR bands	Not included	1617*, 1875, 2185* nm *polarimetric bands (in development)	1617*, 1875, 2185* nm *polarimetric bands
Multiangle views	0º-70º views, 9 angles	-67º to + 67º views on a gimbaled camera 9 discr. angles or a “continuous sweep”	0º-70º views, 9 angles + gimbaled camera
Polarimetry	Not included	0.5% DOLP uncertainty	0.5% DOLP uncertainty
Spatial resolution	275 m – 1.1 km	7m – 20 m depending on the view angle	125 m – 2.2 km
Global coverage	9 days	NA - Targeted area only 11 km x 10 km	4 days (off nadir); 2 days (nadir)

MSPI requirements derived from Aerosol Science Working Group for the Aerosol-Cloud-Ecosystem (ACE) mission

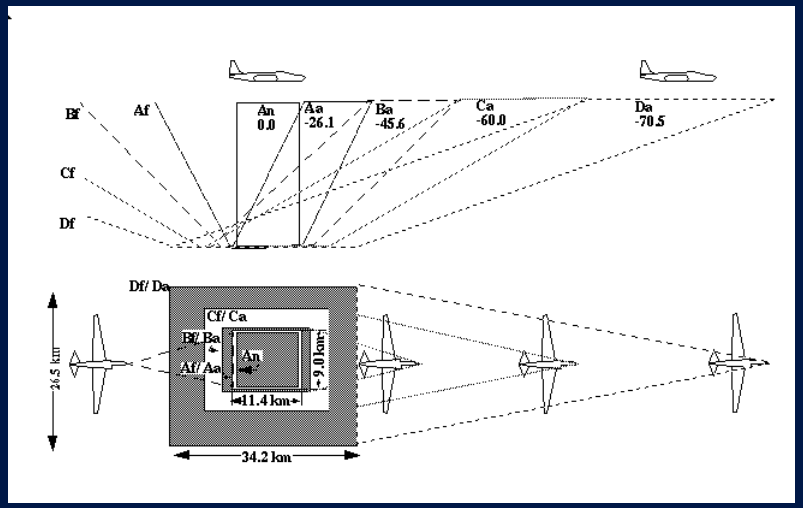
Data Capture and Processing System

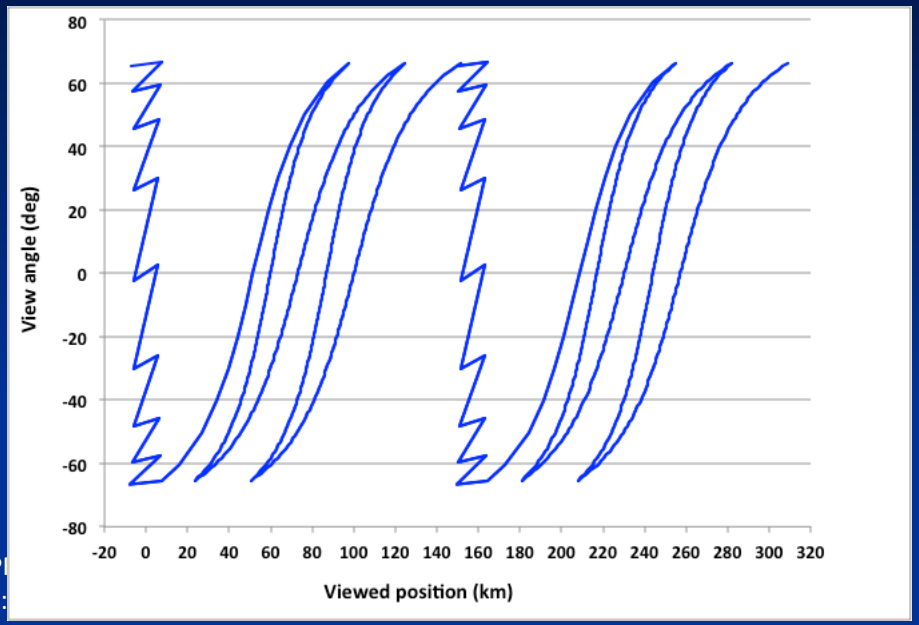


Data Capture

- Instrument
  - Consist of Photo-elastic modulators (PEMs) which time-modulate the Stokes components and encodes information about intensity I and Q and U. So for each detector array that is overlain by polarization analyzer 0^o or 45^o it encodes Q/I and U/I. In the intensity only channels I is unmodulated.
  - It is mounted on a gimbal inside a pressure vessel; driven by an Aerotech actuator equipped with a precision angle encoder, enabling flexible operating and camera pointing modes.
- On-Board processing
  - Simultaneously records and timestamps instrument data from the AirMSPI camera, attitude and position from the ARINC-429 navigation board, and view angle from the Aerotech gimbal controller.
  - It also monitors the pilot cockpit switches and indicates instrument status via the cockpit control panel.
  - Produces data at a rate of 25 MB/s over CameraLink to a dedicated IO Industries frame grabber. Directly attached to the frame grabber is 1TB of Solid State Disk (SSD).
- Planning and commanding
  - Determines the ER-2 flight lines and target locations; calculates the way points at which the pilot is to depress a cockpit switch that activates the gimbal motion and instrument data collection.
- Calibration
  - Radiometric transfer curve is established in the laboratory by using a 1.65m integrating sphere as the illumination source; measurements of the sphere intensity are obtained from a photodiode radiance standard calibrated against a NIST traceable incandescent lamp, and a scanning spectrophotometer; Dark offset levels are obtained in flight by recording data when the camera is stowed.
  - Uses a laboratory polarization state generator (PSG); Illumination from light emitting diodes (LEDs) is depolarized, collimated, and transmitted through a tiltable plane-parallel glass plate to generate partially polarized light. Rotation of the high-extinction polarizer in 10º steps provides the necessary observations. Requirement of DOLP uncertainty of < ±0.005.

Flight Configurations Example





1. Nominal “Step and Stare” mode
2. Experimental “Continuous Sweep” mode

Data Products

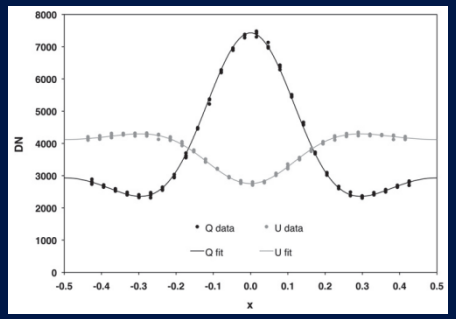
- Nine files per nine view angles in the case of a nominal target; 93 data layers in the single file; HDF-EOS files with sizes of 2MB – 6 MB
- Map projected to a UTM grid with common origin for all views and data layers; Ancillary geocoding per pixel also provided.
- 10 m resolution for nadir and near nadir. 20 m resolution for off nadir angles.

Table 1: AirMSPI data layers within a single HDFEOS file

Parameters / Spectral Bands(grid)	335 nm	380 nm	445 nm	470 nm	555 nm	660 nm	865 nm	935 nm	Anc.
Intensity; Radiometric Data Quality Indicator (RDQI) ; Mask 335 nm	Y	Y	Y	Y	Y	Y	Y	Y	Lat Lon
Degree of Linear Polarization (DOLP)				Y		Y	Y		
Angle of Linear Polarization (AOLP) re. scattering plan				Y		Y	Y		
Angle of Linear Polarization (AOLP) re. meridian plane				Y		Y	Y		
Stokes parameter Q: 1) re. scattering plane, 2) re. meridian plane; Q mask,				Y		Y	Y		
Stokes parameter U: 1) re. scattering plane, 2) re. meridian plane; U mask				Y		Y	Y		
View Zenith; View Azimuth	Y	Y	Y	Y	Y	Y	Y	Y	
Sun Zenith; Sun Azimuth	Y	Y	Y	Y	Y	Y	Y	Y	
Time	Y	Y	Y	Y	Y	Y	Y	Y	

Key processing steps

- Initial data reduction / radiometric calibration



- Reduction from as acquired sub-frames into frames
- Signal consist of constant (I) and modulated (Q or U) components.
- Enabled by the modulation properties of PEM's
- With precise timing modulated components are modeled by Bessel functions varying in amplitude as a function of time
- One cycle per frame ~ 44 ms (~24 subframes per frame

q = (Q/I) and u (U/I)

Diner, D.J., A. Davis, B. Hancock, S. Geier, B. Rheingans, V. Jovanovic, M. Bull, D.M. Rider, R.A. Chipman, A. Mahler, and S.C. McClain (2010). Appl. Opt. 49, 2929-2946.

- Co-registration and Mapping

- Final polarimetric calibration / data reduction

- 1. Apply polarization calibration coefficients

2. Compute polarization parameters

$$DOLP = \sqrt{q^2 + u^2}$$

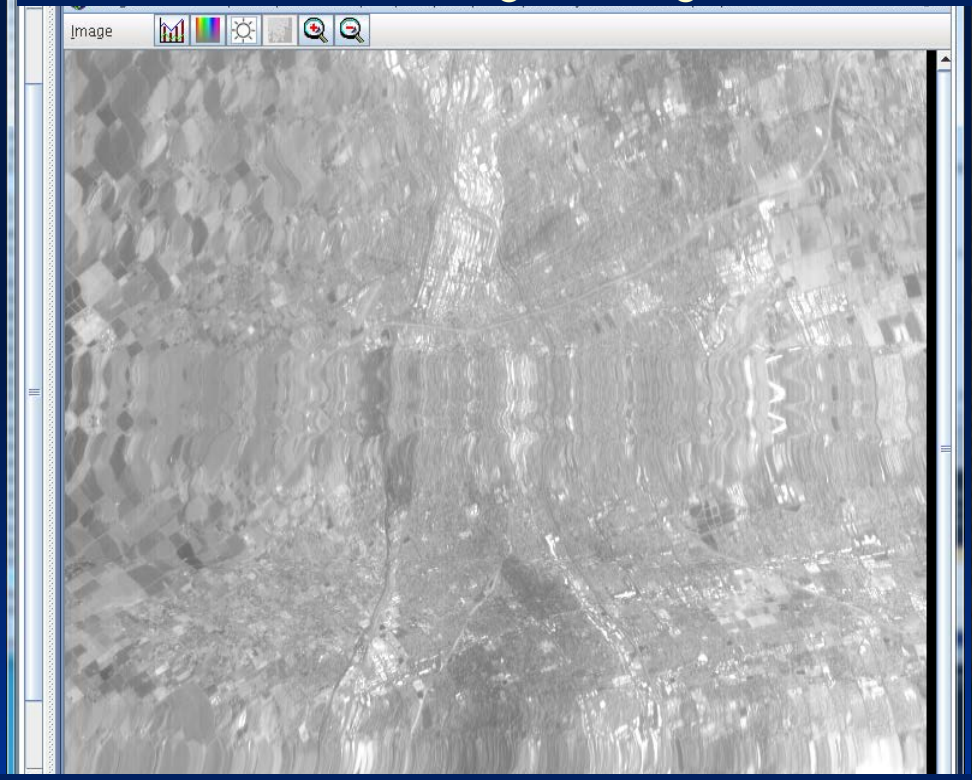
- $$AOLP = \frac{1}{2}\tan^{-1}\left(\frac{u}{q}\right)$$

q, u are adjusted as to be referenced to either scattering or meridianal plane

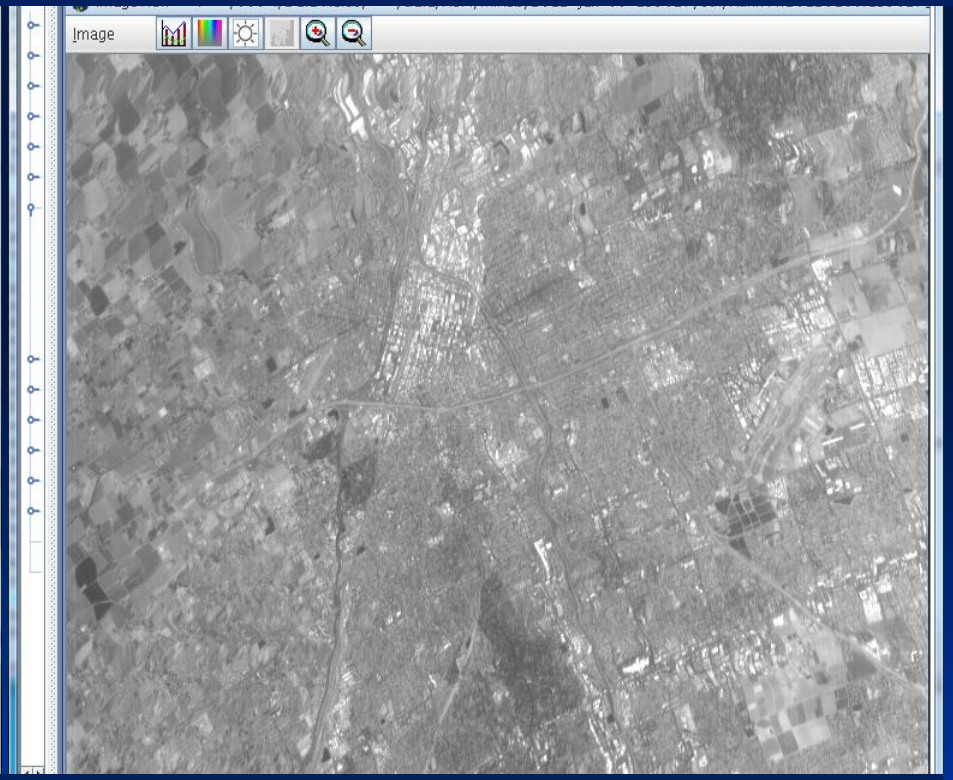
L1B1 input image into co-registration and mapping

- Initially as acquired imagery is distorted. Individual spectral and polarimetric channels within a view angle are mis-registered.

+ 67 deg. view angle



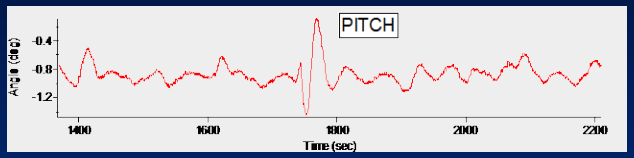
+ 47.5 deg. view angle

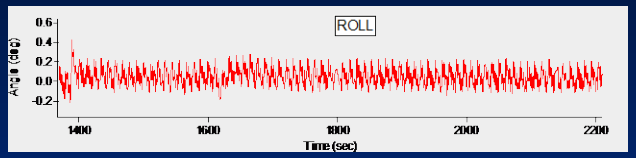


- All data from individual detector line arrays from all nine view angle are to be geo-located and orthorectified to satisfy mapping accuracy of 0.5 pixels or better.

Other ancillary input ---------- $\vec{\rho} = T_{Ea}T_{ag}T_{\bar{g}}T_{gc}\vec{r}_c$

- Camera Geometric Model $\overrightarrow{-r_c}$
  - Pixels pointing direction relative to the camera coordinate system defined by image line and sample coordinates and: 1) pairs of polynomials converting real to paraxial image coordinates accounting for optical aberrations, 2) EFL, and 3) Principal Point
- Gimbal pointing – $T_{ag}T_{\bar{g}}T_{gc}$
  - Orientation of the gimbal around its pitch axis with the angle provided by the assembly and on-board processing. Assumed alignment between gimbal axis and camera axis. Orientation of gimbal are relative to the ER-2 attitude reference coordinate axis is to be calibrated in-flight.
- ER-2 Navigation Data – T_{Ea}
  - Provides for orientation between ER-2 and Earth geocentric coordinates axis.





Parameter	Res.	Accuracy	Propagated Error
Roll/Pitch.	64 Hz	0.05 deg	20 m nadir 170 m most oblique
Yaw (True Heading)	64 Hz	0.4 deg	60 m end of FOV
Altitude	32 Hz	40 m	13 m nadir 120 m most oblique
Horiz. Pos.	1 Hz	30 m	30 m

- Geometric Ground Truth - G_{gcp}
  - USGS DEM with resolution of 1m posting over US and 30 m (TBD)
  - USGS 4 m DOQ and high resolution high altitude imagery … (TBD)

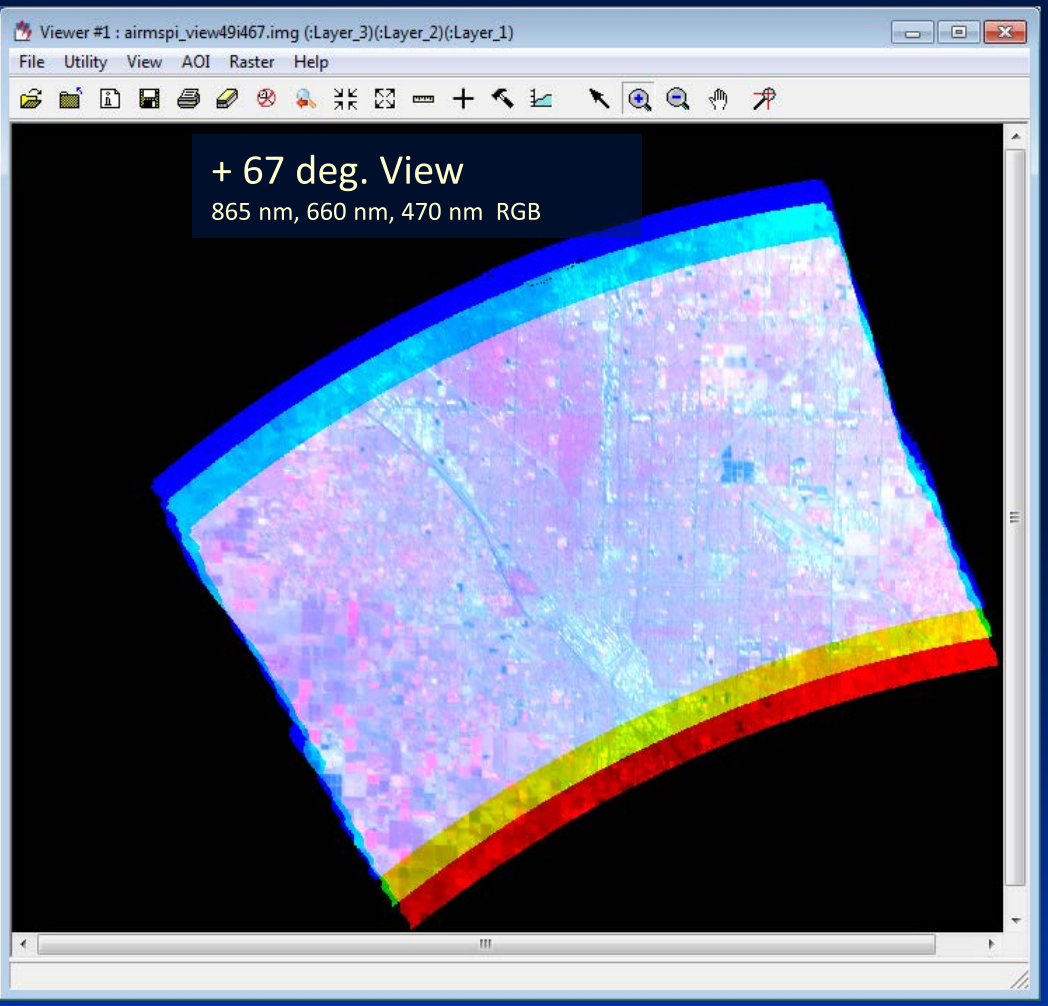
Algorithm

- 1. Ray Casting algorithm - imagery projected to the underlying DEM using supplied data to form initial orthorectified image.

- 2. GCP's and suitable tie points extracted and identified across multi-angle imagery.
  - Using a combination of feature extraction, cross-correlation, and least-square matching algorithms.
  - Initially orthorectified imagery used to matching to overcome large initial distortions. Backward projection used to relate to time-dependent navigation data.

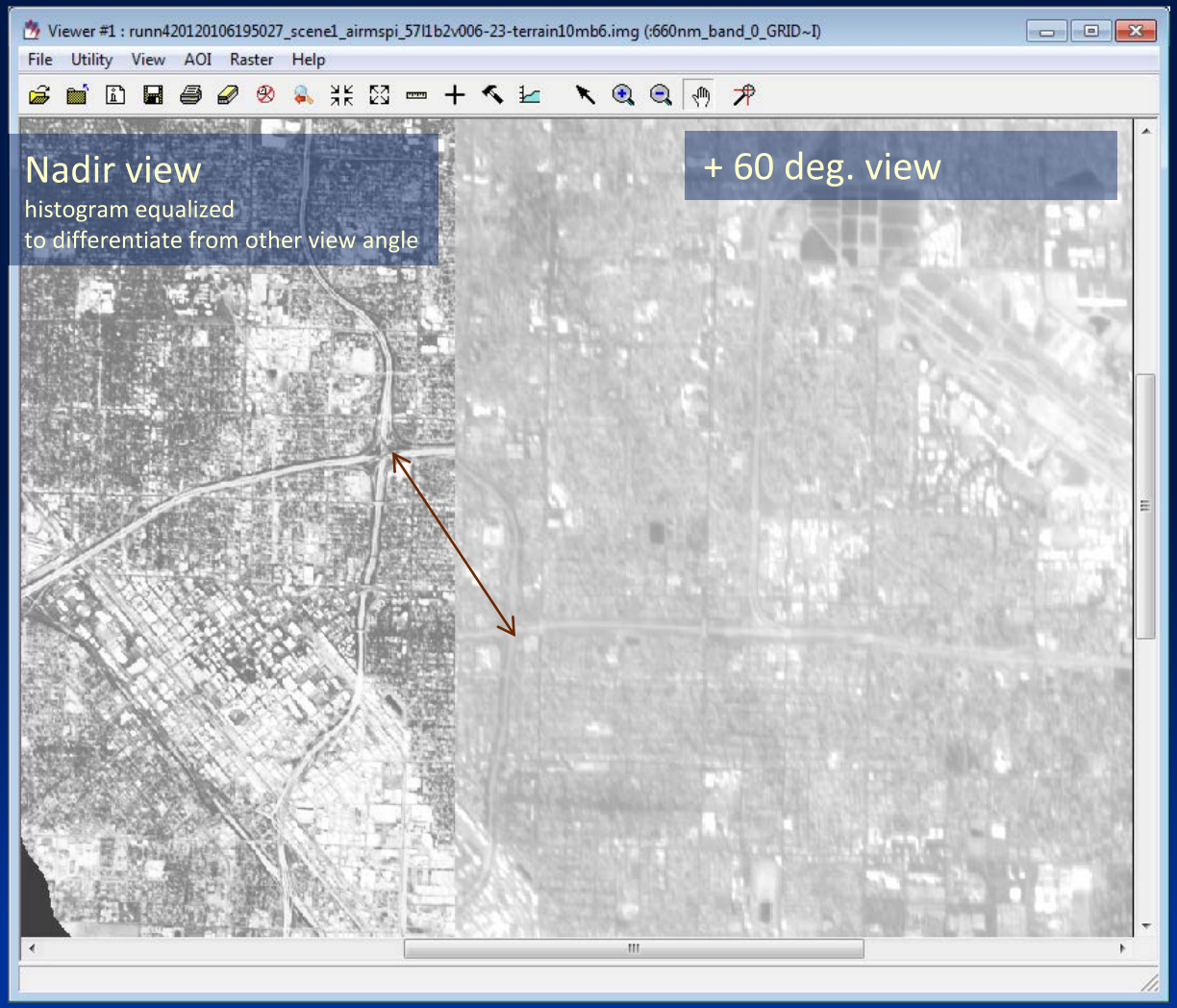
- Simultaneous bundle adjustment solves for the parameters of interest by a non-linear lest square $\lambda \overrightarrow{\rho} = G_{gcp} - P_a$.
  - Static corrections of gimbal assembly
  - Dynamic corrections modeled as piecewise linear with respect to time for positions and ER-2 attitude.

Results 1 - no adjustment band-to-band co-registration



By using as supplied navigation data and nominal camera geometric model band to band co-registration looks good.

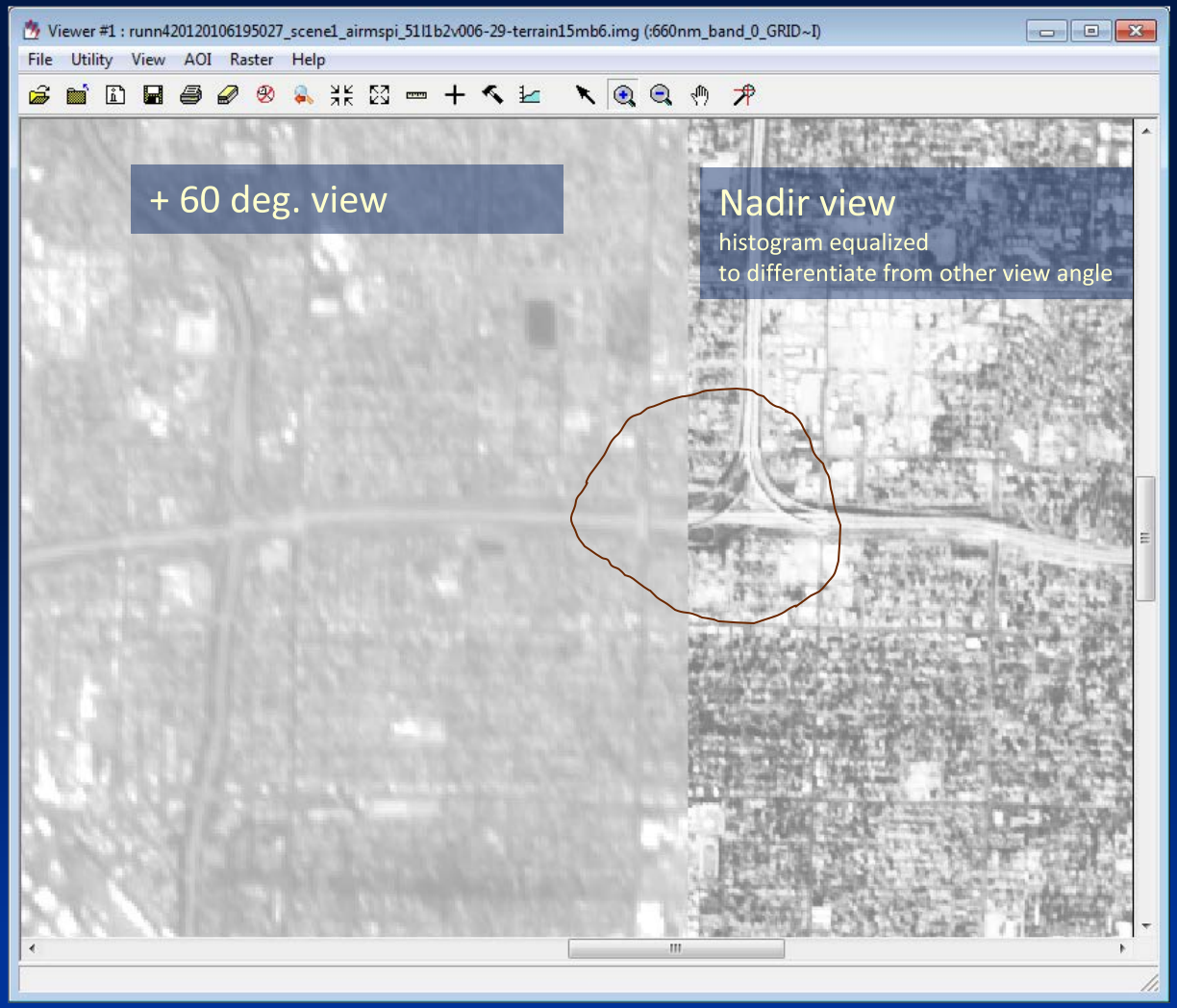
Results 1 - no adjustment co-registration



Images from nadir and + 60 deg. view angle are overlaid on the same map projection grid. A "swipe" technique used to visualize co-registration error.

By using as supplied nominal data multi-view co-registration errors of up to still few km exist.

Results 2 – static camera geometric model correction

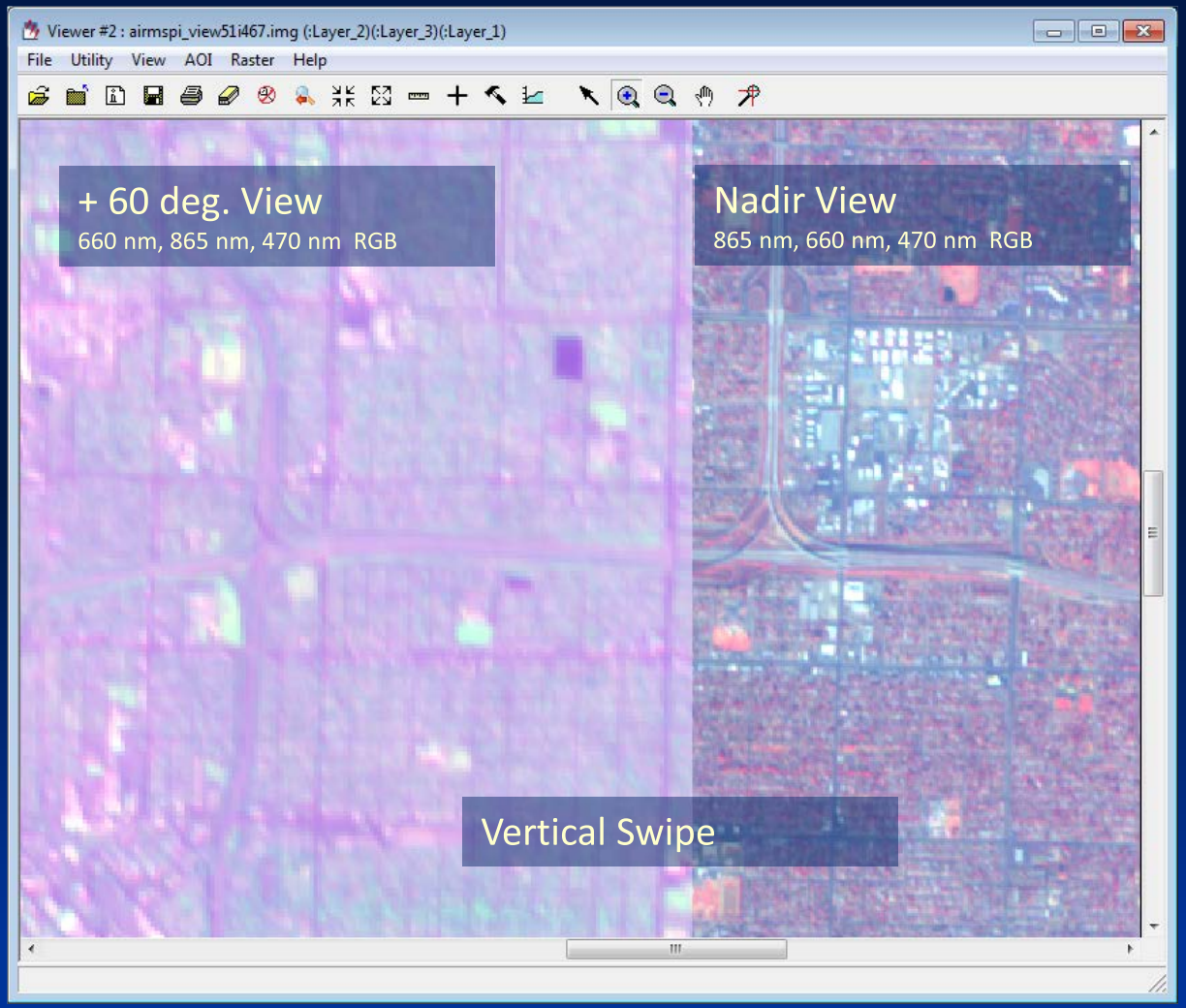


Images from nadir and + 60 deg. view angle are overlaid on the same map projection grid. A "swipe" technique used to visualize co-registration error.

By applying "static" camera model corrections errors reduced around 100 m.

Camera Geometric Model Corrections:
Yaw = + 0.084 deg.
Pitch = - 1.911 deg.
Roll = -1.390 deg.

Results 3 - Final



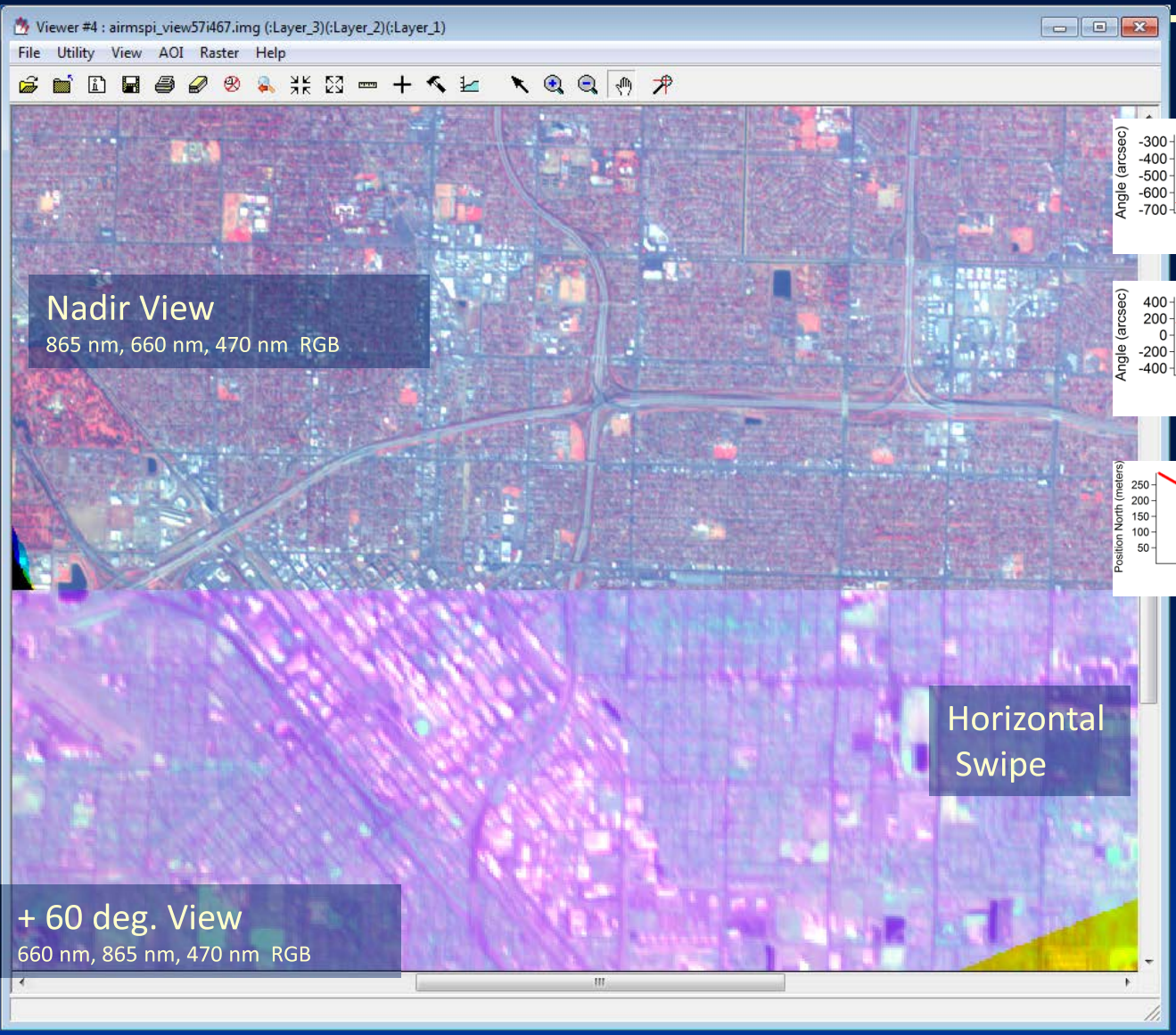
Images from nadir and + 60 deg. view angle are overlaid on the same map projection grid. A "swipe" technique used to visualize co-registration error.

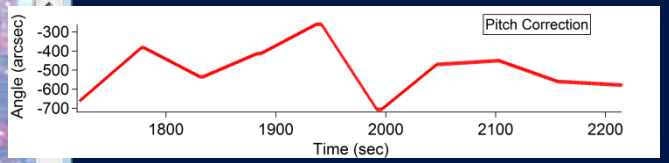
By applying "static" camera model corrections plus time dependent nav. data correction errors reduced to subpixel levels of around 5 – 10 m.

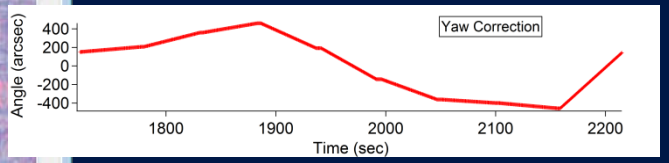
Camera Geometric Model Corrections:
Yaw = + 0.084 deg.
Pitch = - 1.911 deg.
Roll = -1.390 deg.

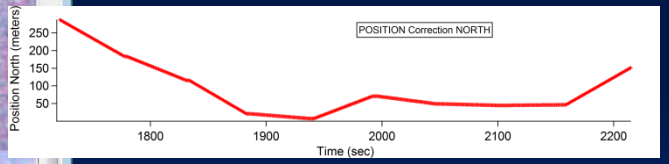
Plus
Time-dependent piecewise linear for position and attitude

Results 3 – Final









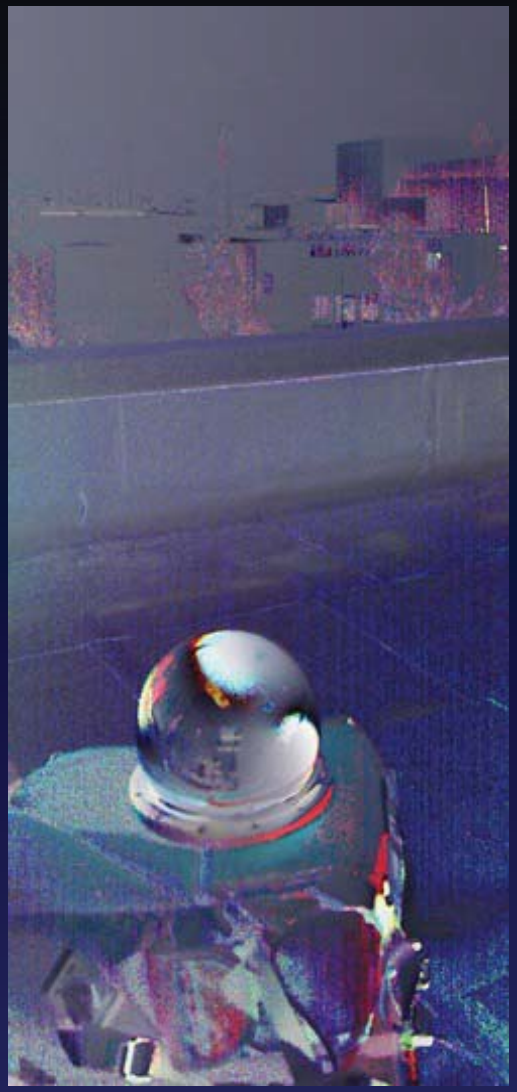
Scientific applications

- The Earth Sciences Decadal Survey (National Research Council, 2007) calls for "a highly accurate multiangle-multiwavelength polarimeter to measure cloud and aerosol properties [that] would have a cross-track and along-track swath with ~1 km pixel size."
- Integration of multiple view angles, multispectral measurements, and polarimetry is a powerful method of sensing the microphysical and optical properties of airborne particles.
- AirMSPI serves as a prototype for a speceborne MSPI that fits the requirements and its also applicable to aerosol and cloud remote sensing at much higher spatial resolution.
- EXAMPLES …

Examples GroundMSPI

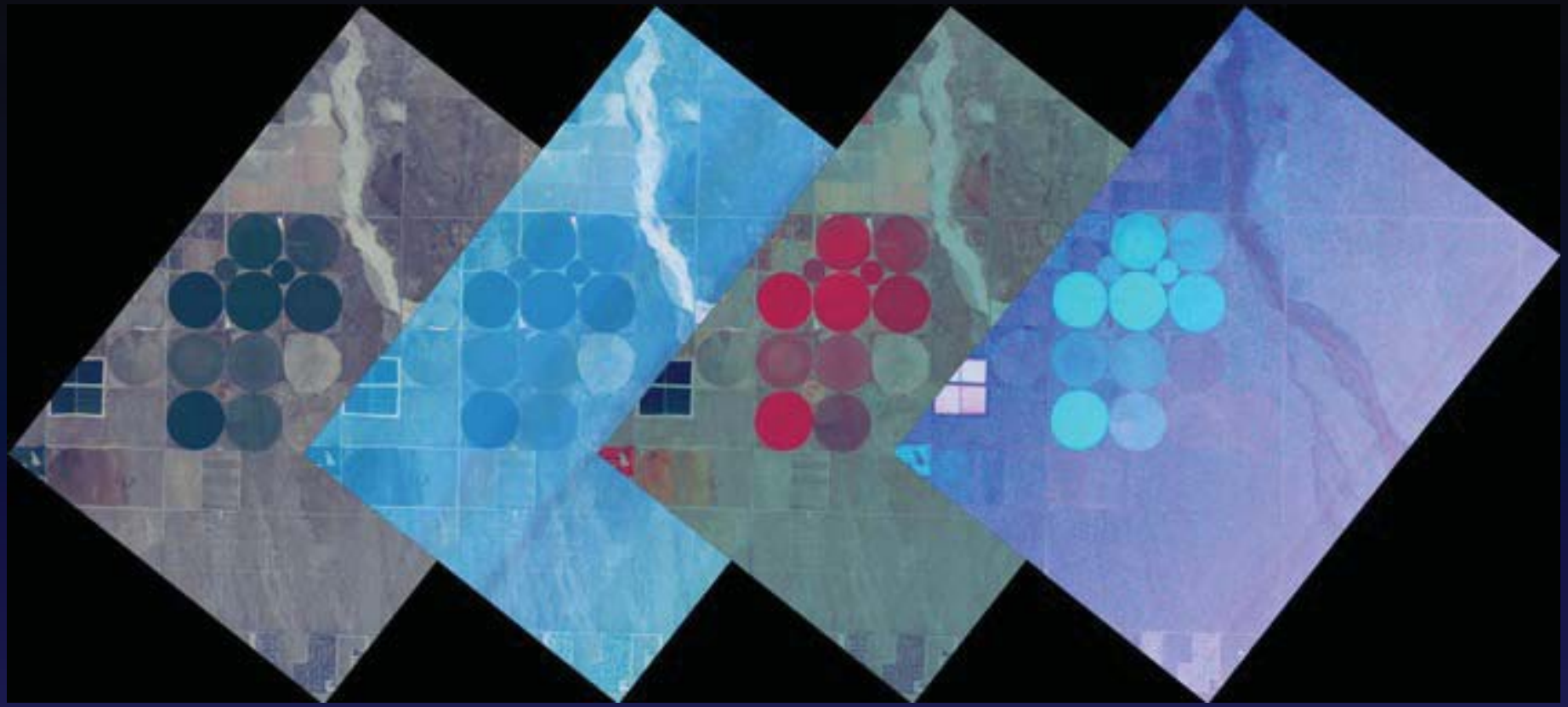
470, 660, 865 nm Intensity

470, 660, 865 nm DOLP



470, 660, 865 nm AOLP

Examples AirMSPI first flight imagery – Palmdale October 7, 2010

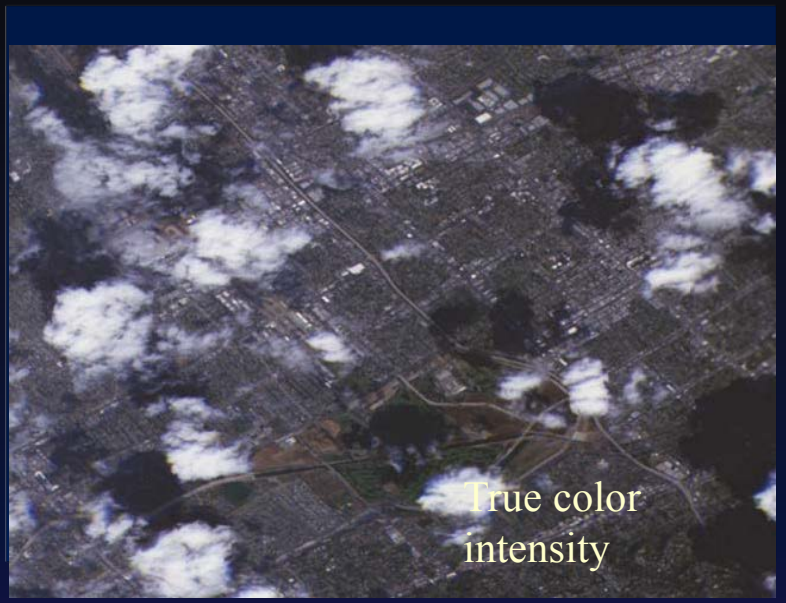


Radiance	Radiance	Radiance	DOLP
445, 555, 660	355, 380, 445	470, 660, 865	470, 660, 865

Example - Clouds in polarized light

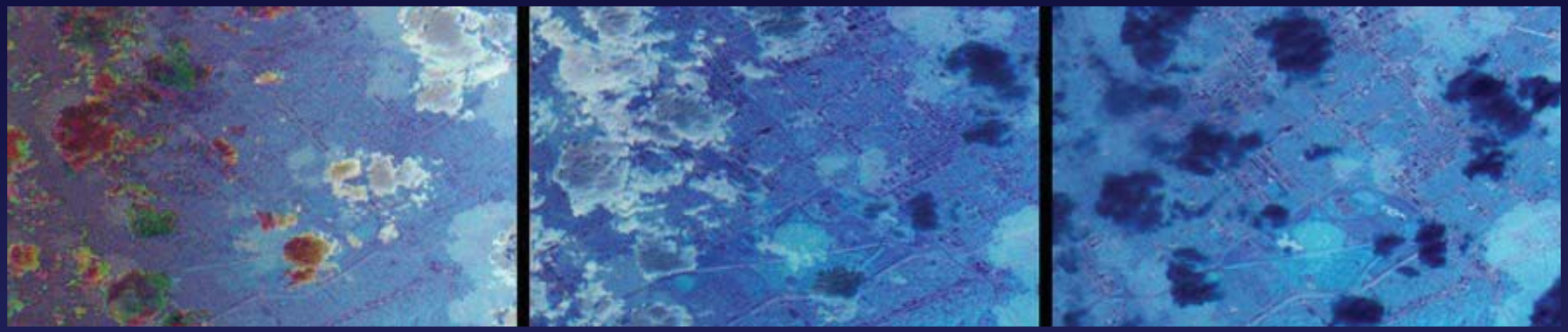
AirMSPI imagery over
Van Nuys, CA

DOLP, 470, 660, 865 nm



Supernumerary bows

cloudbow



170º 145º increasing backscatter 110º

Example - a "continuous sweep" sequence on August 31, 2011 off the coast of California.

San Clemente Island