PASSIVE MILLIMETER WAVE IMAGING WITH SUPER-RESOLUTION: Application to Aviation safety in extremely poor visibility

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PASSIVE MILLIMETER-WAVE IMAGING (PMMWI) PROJECT: OBJECTIVES &GOALS

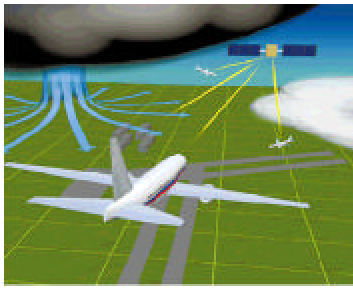
- **Explore the potential application of Radiometric sensors to alleviate atmospheric hazards to aviation.**

- **Develop/design an all-weather Radiometer operating at 94 GHz which employs Super-Resolution Algorithms for a Real -Time rapid image inversion processing, and is capable of producing very high resolution images (recover scene-spatial frequencies ~or >10 X {Rayleigh Limit}).**

- **Construct a functioning system capable of Ground and Airborne Applications**

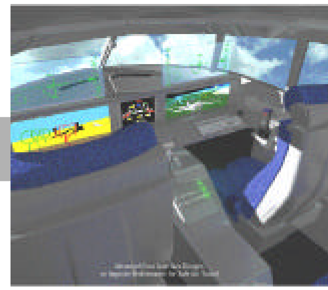
Aeronautics & Space Transportation Technology Strategic Roadmap

***Pillar One*: Global Civil Aviation**

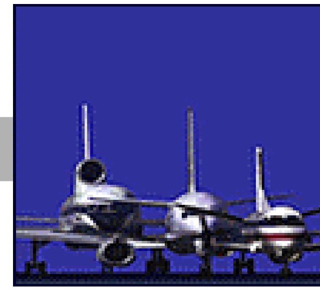


Safety

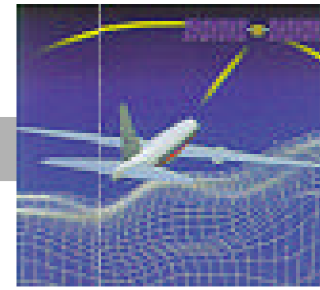
2000



Human-Related Factors

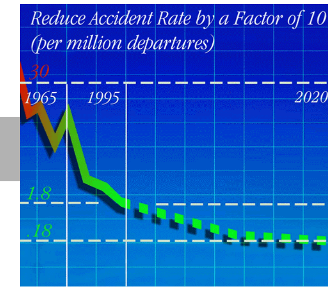


Increase Airport Capacity



Improve Navigational Aids

2010



Reduce Accident Rates 10X

Millimeter Wave Radiometry at 94 GHz with Super-Resolution

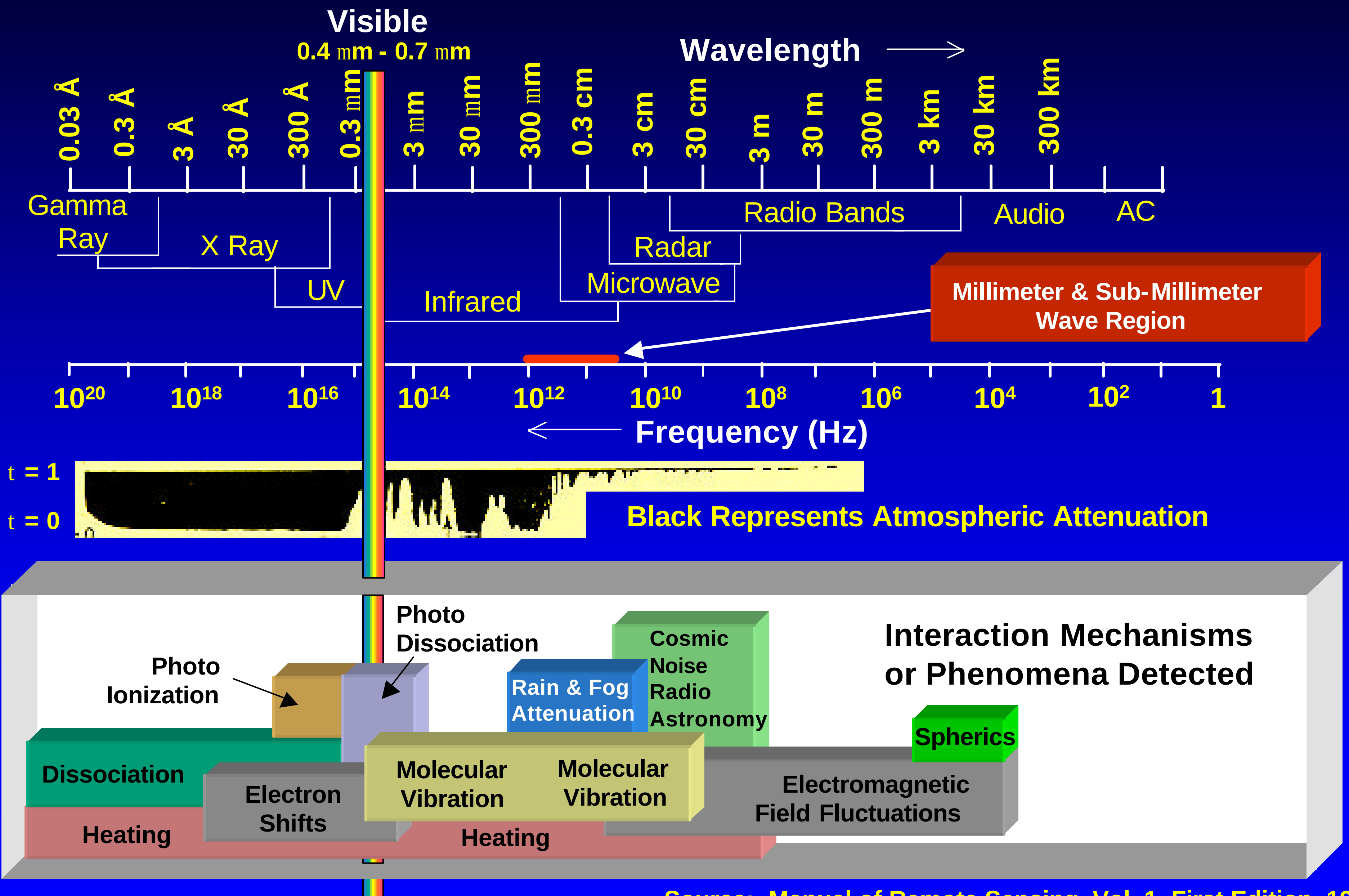
- **Structurally Embeddable**
- **Low Power Applications**
- **Payload Reduction**
- **Compact**

Space Applications

Remote Sensing of Planetary Surfaces

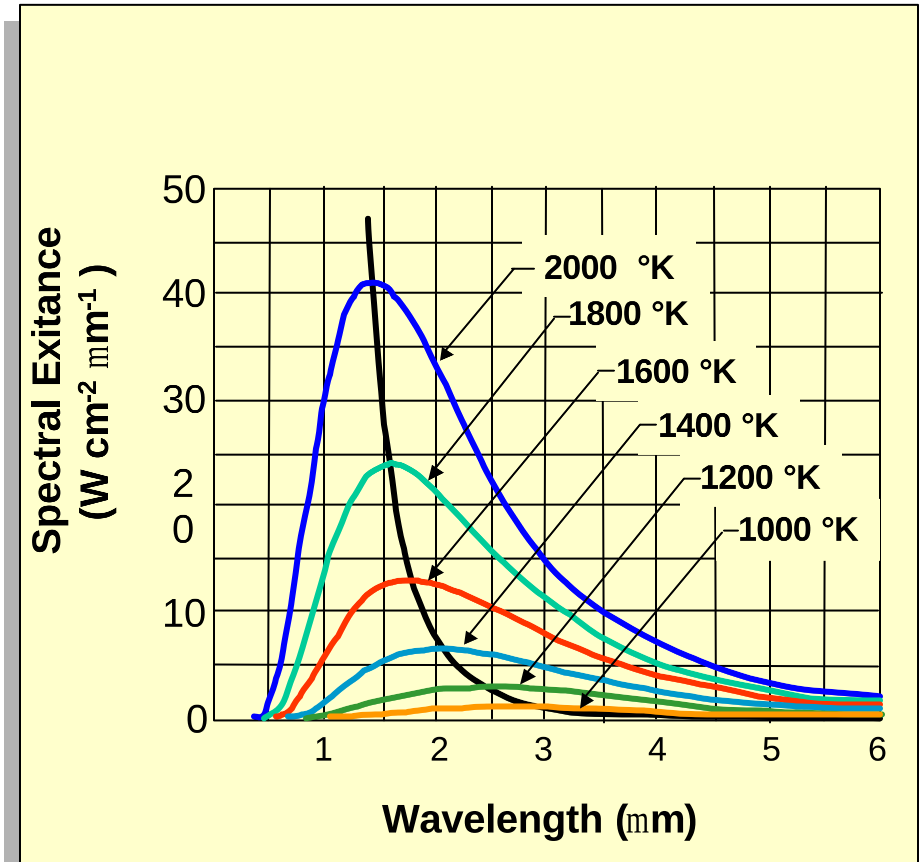
Source: Aeronautics & Space Transportation Technology / Strategic Roadmap, NASA GRC

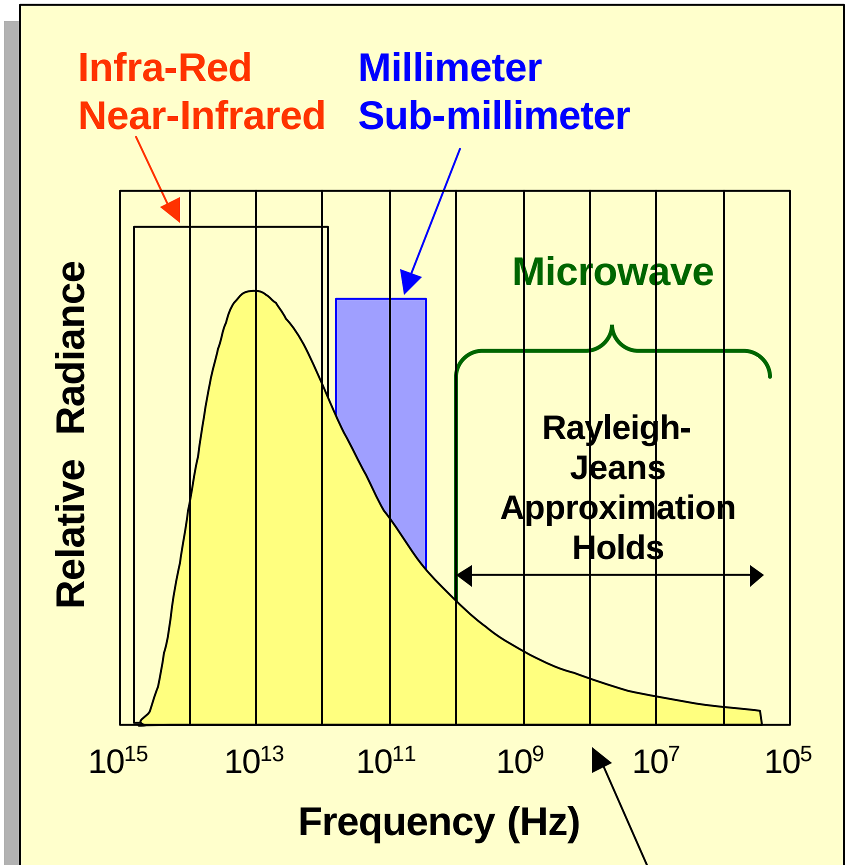
Electromagnetic Spectrum



Source: Manual of Remote Sensing, Vol. 1, First Edition, 1975

Black Body Radiation





$$B_{bb} = \frac{2f^2kT}{c^2} = \frac{2kT}{l^2}$$

Why Passive Millimeter-Wave Imaging?

- All natural objects whose temperatures are above absolute zero emit passive millimeter-wave radiation.
- **Millimeter-waves are much more effective (lower attenuation) than infrared in poor weather conditions such as fog, clouds, snow, dust-storms and rain. Also, images produced by passive millimeter-waves have natural appearances.**
- The amount of radiation emitted in the millimeter-wave range is 10^8 times smaller than the amount emitted in the infrared range.
- However, current millimeter-wave receivers have at least 10^5 times better noise performance than infrared detectors and the temperature contrast recovers the remaining 10^3.
- This makes millimeter-wave imaging comparable in performance with current infrared systems.
- Electromagnetic radiation windows occur at 35 GHz, 94 GHz, 140 GHz, and 220 GHz.
- Choice of frequency depends on specific application

APPLICATIONS

REMOTE SENSING
(Terrestrial & Extra-terrestrial)

- **Airport Safety**
- **All-Weather Vision**
- **Fused Sensor Imaging - Component**

DIAGNOSTICS

- **Medical Diagnostics**
- **Plasma Diagnostics**

GENERAL

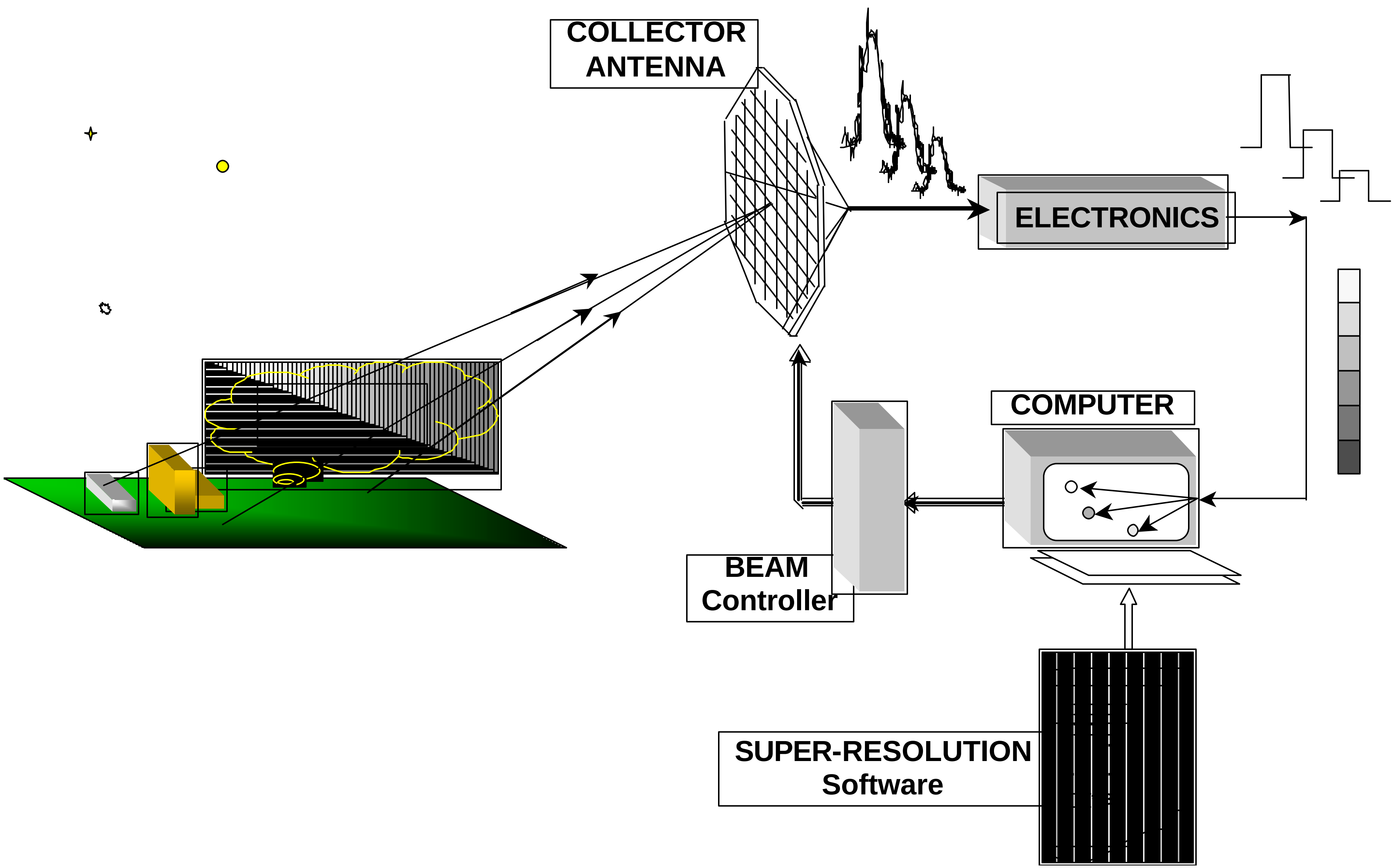
- **In-Situ Non-Destructive Testing**
  (Composites : Voids, Delaminations)
- **Defense Applications**
- **Environmental**

SIDE - BENEFITS

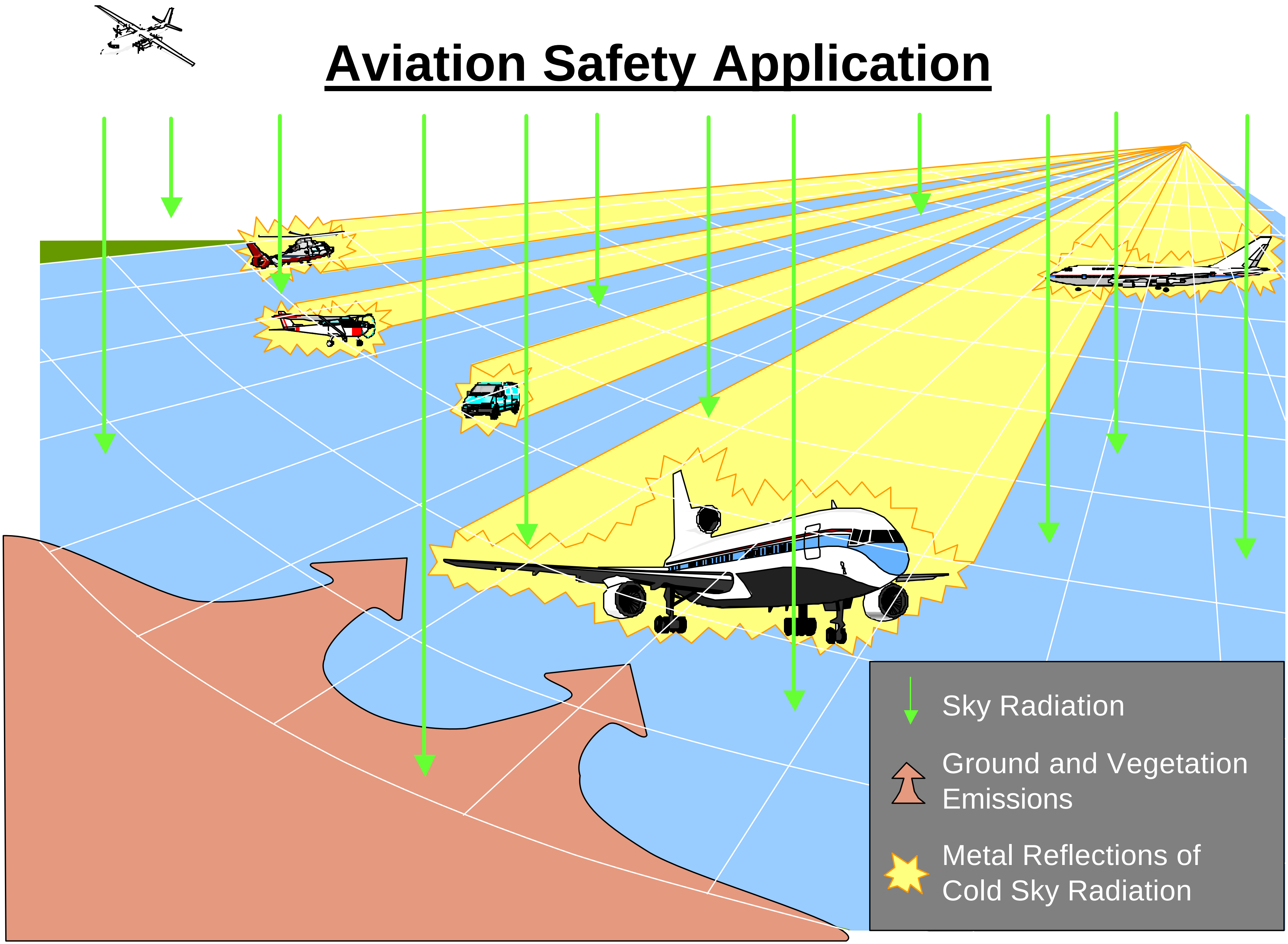
Advances in Inverse Problem Solutions for :

- **Geological Explorations**
- **Remote Sensing of Vegetation & Soil Conditions**
- **Non-Invasive Brain Volumetric Mapping**

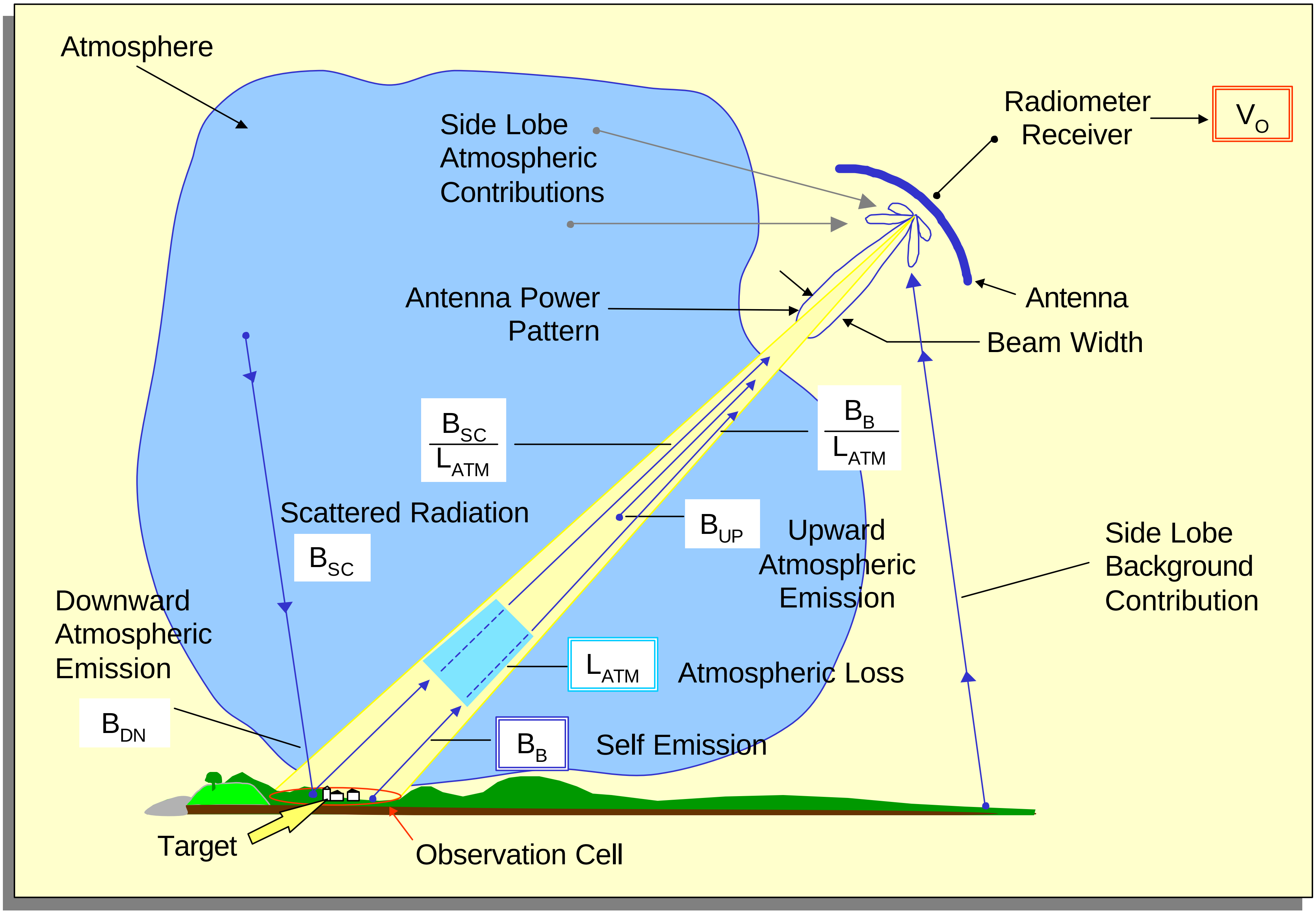
RADIOMETER CONCEPT



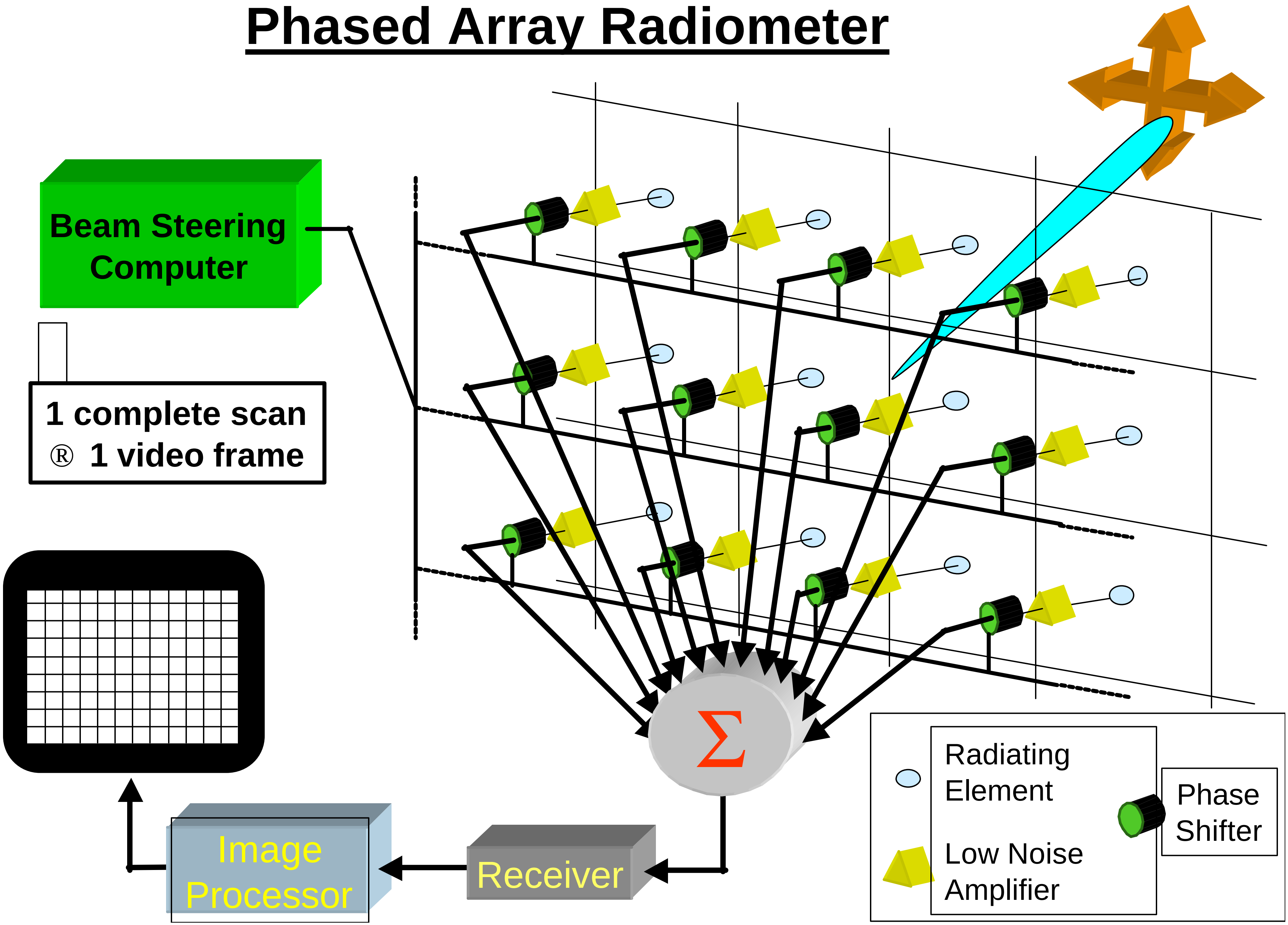
Aviation Safety Application



Passive Radiometric Sensing - Concept

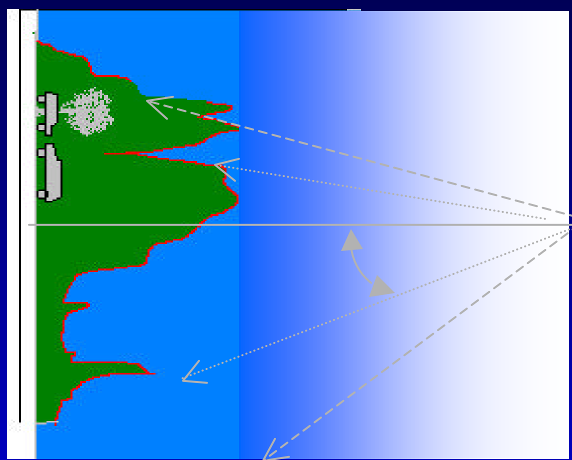


Conceptual Diagram of 2-D Phased Array Radiometer



"True" Scene..Recovery

Direct Measurement Result



GOAL: Best true "Scene " R e c o v e r y

INVERSE Problem Solution

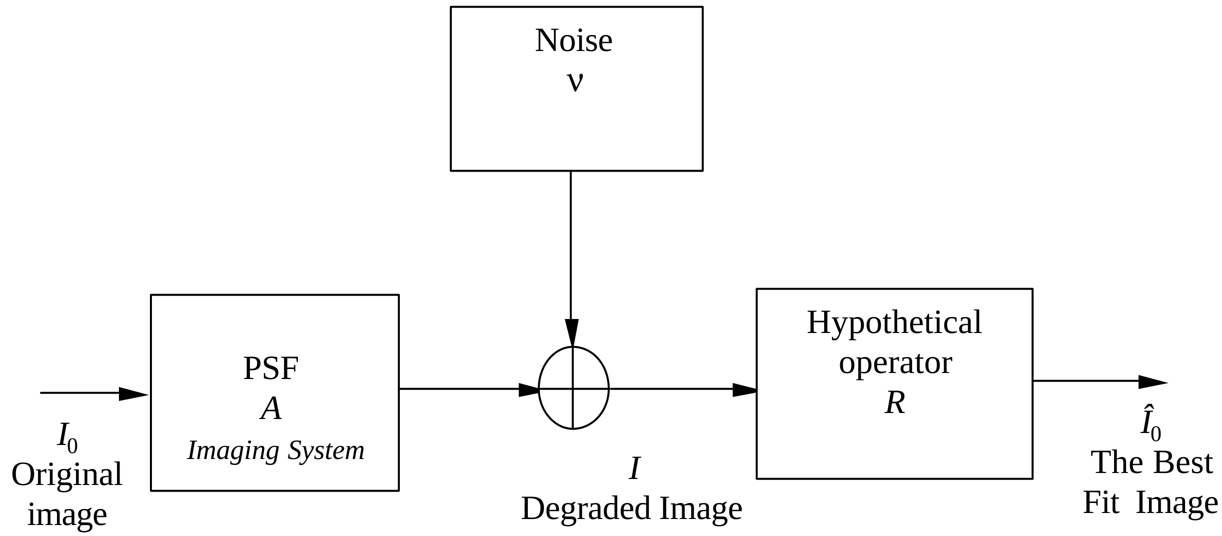
- **EMR-Properties** of Propagation media
- **Mathematical** Processing of Measured Data

TRUE Scene

Why Super-Resolution?

- Images acquired from practical sensing operations usually suffer from poor resolution due to the finite size limitations of the antenna, or the lens, and the consequent imposition of diffraction limits.
- The fundamental operation underlying the sensing operation is the **“low-pass” filtering effect** due to the finite size of the antenna lens.
- The portions of the scene that are lost by the imaging system are the fine details (high frequency spatial spectral components) that accurately describe the object in the scene.
- For super-resolution, **spatial spectral extrapolation** is needed.
- Some studies have indicated that the cost of an imager increases as (1/Resolution) raised to the power 2.5.
- Hence, a possible two-fold improvement in resolution **by super-resolution processing**, roughly translates into a cost reduction of an imager by more than 5 times.

Regularization/Reduction Method



$$I = AI_0 + \nu$$
$$\hat{I}_0 = R\,AI_0 + R\nu = RI$$

The mathematical model of the method is shown above where:
I_0 = is the original image,
I = is the degraded image = $AI_0 + \nu$
A = the measured PSF of the imaging system,
ν = is the measured mean square noise of the system,
R = is a hypothetical operator to be found in order to obtain the best fit image.
RAI_0 = the noise-free output.

The main idea of this method of reduction is to find an operator R such that the following conditions are satisfied:

$$\overline{\|R \cdot n\|^2} \le e \qquad (2.3)$$

$$R(w) = \left(A^* A + w E\right)^{-1} A^* \qquad (2.4)$$

$$\text{and} \quad \min_R \left\{ \overline{\|RA - E\|^2} \Big/ \overline{\|R \cdot n\|^2} \le e \right\} \le d \qquad (2.5)$$

ε =maximum required mean square noise of the system
δ =maximum allowed error for the mean square difference between RA and E (the identity matrix) , A^* is the transposed matrix of A.
ω is a parameter to be found such that the set of conditions (2.3), (2.4) and (2.5) is satisfied. These conditions form a constrained optimization problem.

Mathematics of Inversion : TIKHONOV - PYTIEV Regularization

Errors: $e_1, e_2, e_3, \ldots e_m$

— equal weights

— related by

$$e^2 = \sum_k e_k^2$$

CONSTRAINT
LINEAR INVERSION :

$$f = (A^* A + \gamma H)^{-1} A^* g$$

Tikhonov-Regularization

$$f = (A^* A + \gamma I)^{-1} A^* g$$

Tikhonov - Pytiev Regularization

R operator is chosen so as to make the elements of the transformed error vector **"e "** mutually independent and possessing the same weight

$$A f = g + e$$

$$R A f = R g + R e$$

Minimize $(f^* \cdot H \cdot f))$ subject to constraint

$$|Re|^2 = \text{constant} = \varepsilon^2$$

R operator is subject to 3 conditions :

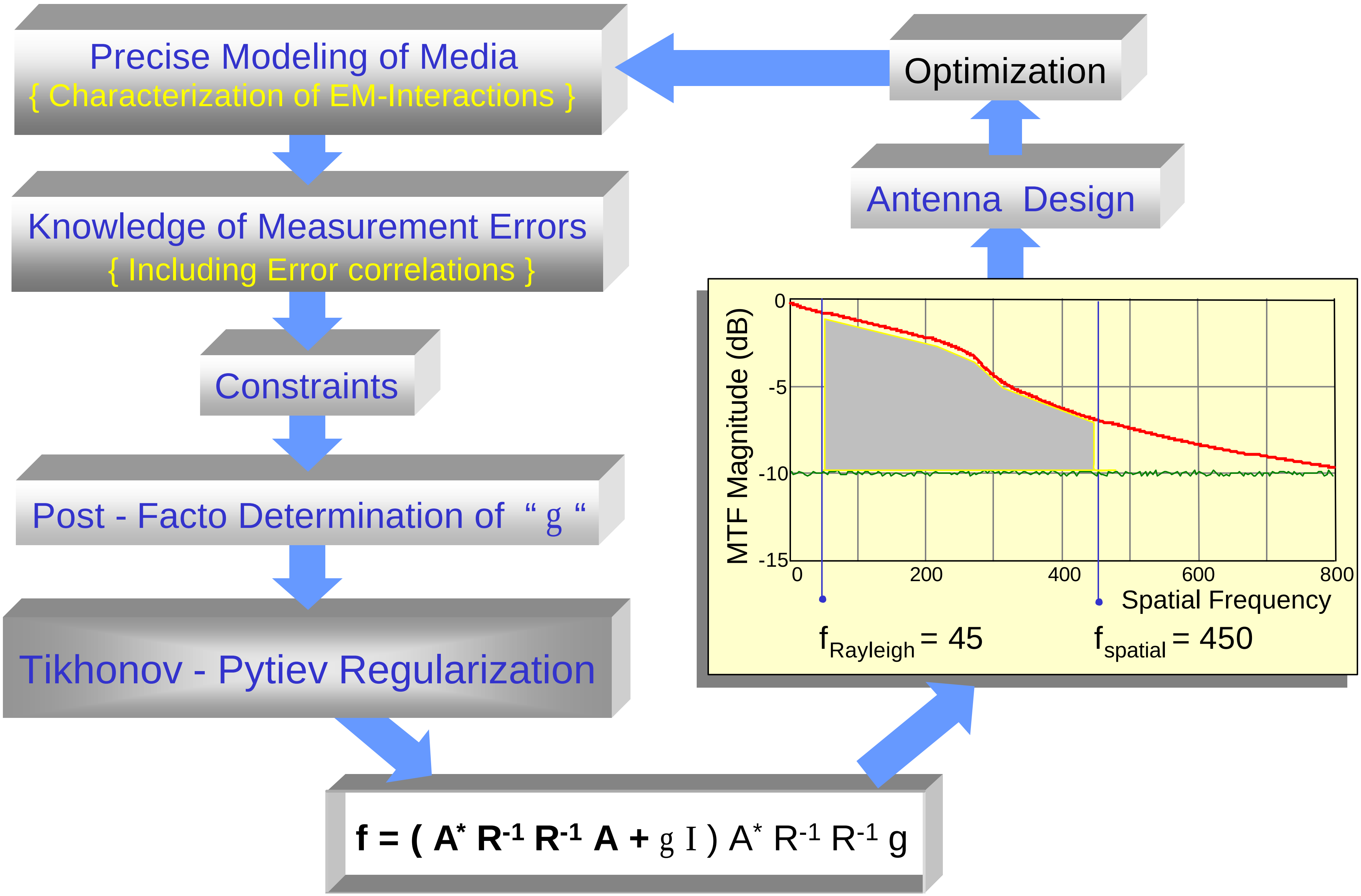
1..angle target size within limits (Fourier image size within the recording system's MTF)

2..signal to noise ratio no more than 3:1(preferably 5:1)

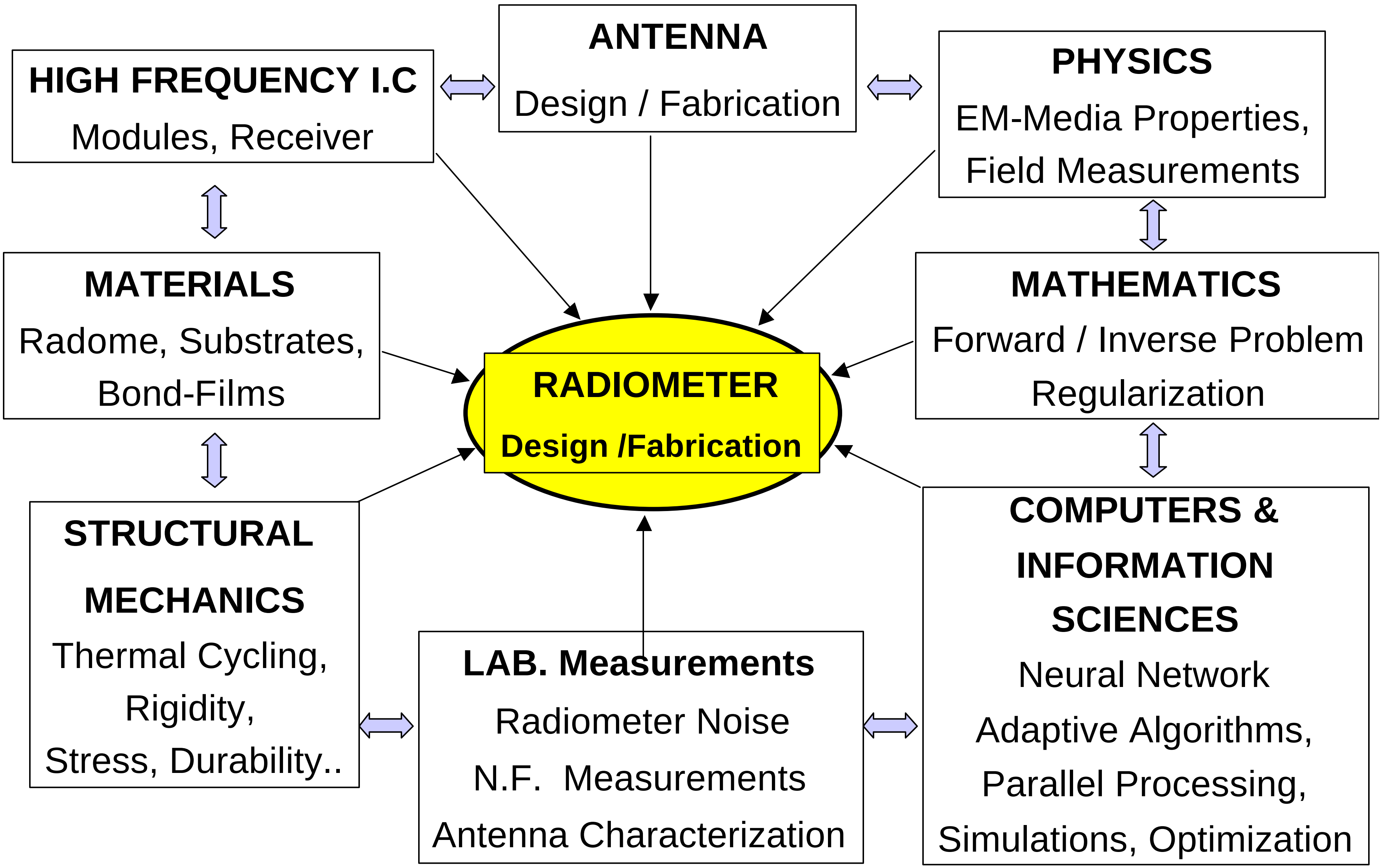
3..antenna scanning limited to avoid Gain degradation and Grating Lobes

$$\mathbf{f = (A^* R^{-1} R^{-1} A + g\ I) A^* R^{-1} R^{-1} g}$$

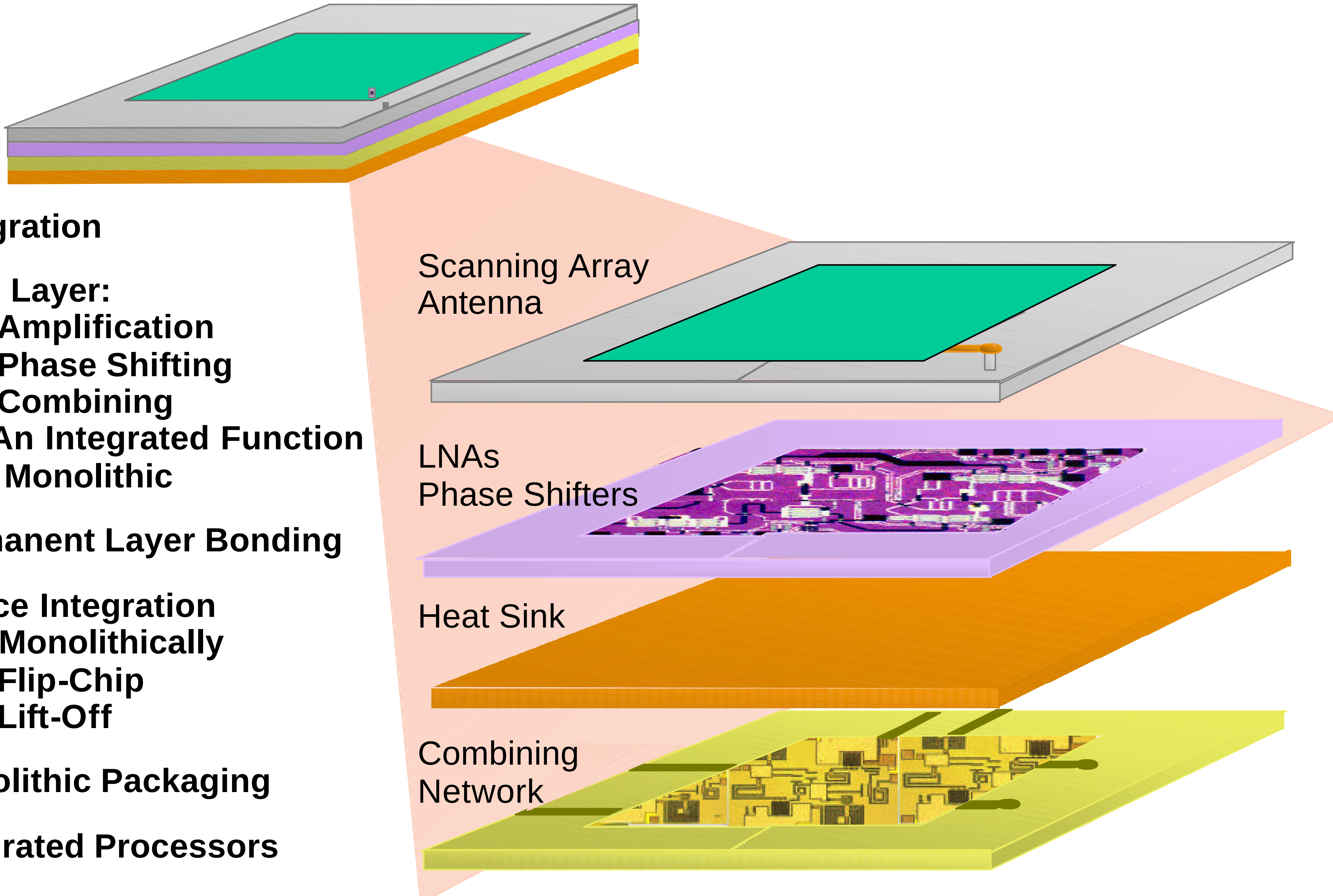
Assembling the Building Blocks...



Multi-Disciplinary Approach



Future Radiometer Trends:
Multi-Layered Integrated System



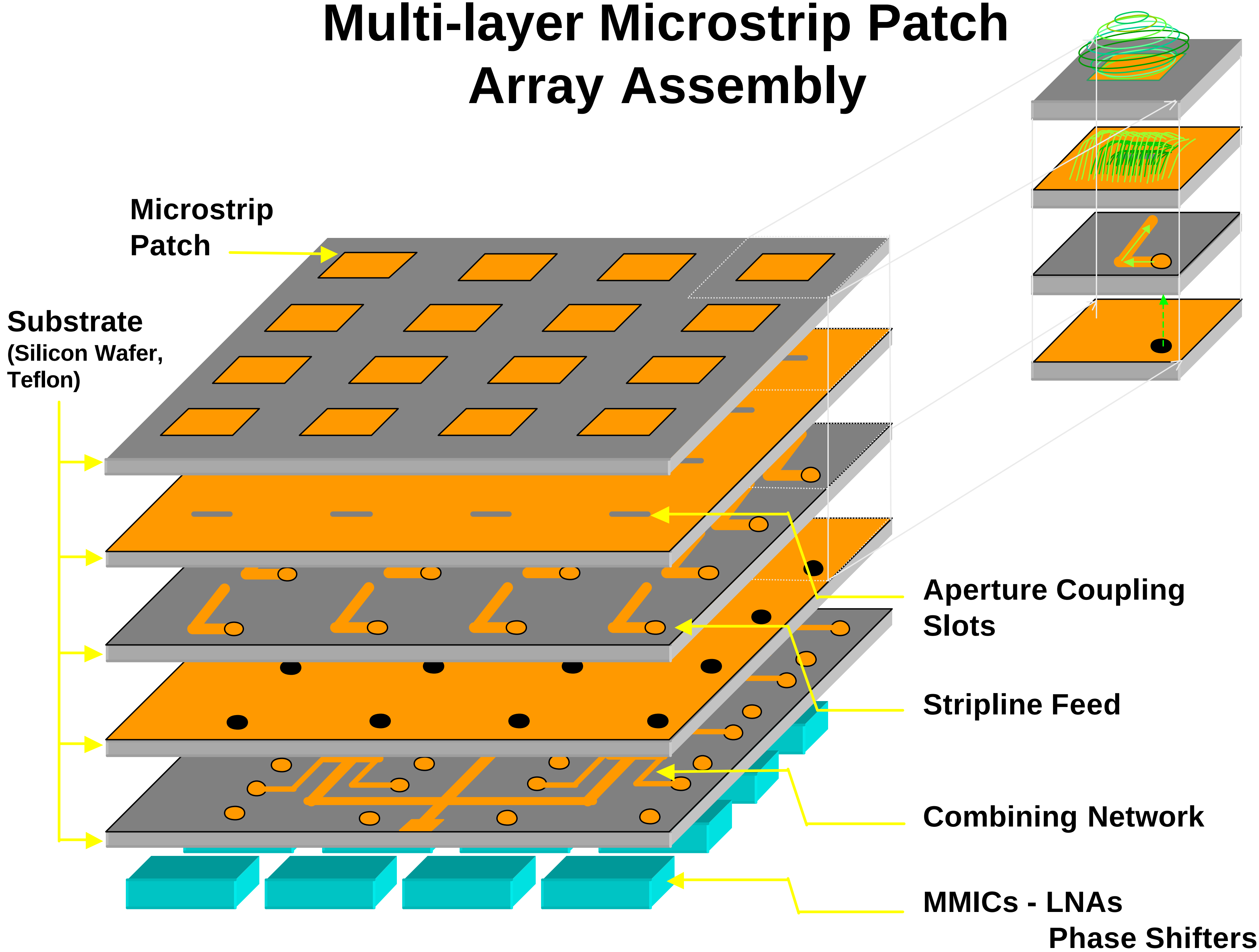
Integration

- **Each Layer:**
  - **Amplification**
  - **Phase Shifting**
  - **Combining**

  Has An Integrated Function
- **High Monolithic**
- **Permanent Layer Bonding**
- **Device Integration**
  - **Monolithically**
  - **Flip-Chip**
  - **Lift-Off**
- **Monolithic Packaging**
- **Integrated Processors**

Source: University of Michigan `http://www.eecs.umich.edu/RADLAB/katehi.dir/cism/index.html`

Multi-layer Microstrip Patch Array Assembly



RESOURCES: SELECTED BIBLIOGRAPHY

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